Published in Journals: Buildings, Forests, Land and Sustainability

Topic Reprint

# Biophilic Cities and Communities

## Towards Natural Resources, Environmental and Social Sustainability

Edited by
Xin-Chen Hong, Baojie He, Jiang Liu, Jinda Qi, Guangyu Wang and Shi Cheng

mdpi.com/topics

MDPI

# Biophilic Cities and Communities: Towards Natural Resources, Environmental and Social Sustainability

# Biophilic Cities and Communities: Towards Natural Resources, Environmental and Social Sustainability

Topic Editors

**Xin-Chen Hong**
**Baojie He**
**Jiang Liu**
**Jinda Qi**
**Guangyu Wang**
**Shi Cheng**

MDPI

Basel • Beijing • Wuhan • Barcelona • Belgrade • Novi Sad • Cluj • Manchester

*Topic Editors*

Xin-Chen Hong
School of Architecture and Urban-Rural Planning
Fuzhou University
Fuzhou
China

Baojie He
School of Architecture and Urban Planning
Chongqing University
Chongqing
China

Jiang Liu
School of Architecture and Urban-Rural Planning
Fuzhou University
Fuzhou
China

Jinda Qi
Department of Architecture
National University of Singapore
Singapore
Singapore

Guangyu Wang
Faculty of Forestry
University of British Columbia
Vancouver
Canada

Shi Cheng
School of Architecture
Southeast University
Nanjing
China

*Editorial Office*
MDPI AG
Grosspeteranlage 5
4052 Basel, Switzerland

This is a reprint of the Topic, published open access by the journals *Buildings* (ISSN 2075-5309), *Forests* (ISSN 1999-4907), *Land* (ISSN 2073-445X) and *Sustainability* (ISSN 2071-1050), freely accessible at: https://www.mdpi.com/topics/KX5WREG227.

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

Lastname, A.A.; Lastname, B.B. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

**ISBN 978-3-7258-4093-9 (Hbk)**
**ISBN 978-3-7258-4094-6 (PDF)**
**https://doi.org/10.3390/books978-3-7258-4094-6**

Cover image courtesy of Dan-Yin Zhang

© 2025 by the authors. Articles in this book are Open Access and distributed under the Creative Commons Attribution (CC BY) license. The book as a whole is distributed by MDPI under the terms and conditions of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) license (https://creativecommons.org/licenses/by-nc-nd/4.0/).

# Contents

**About the Editors** . . . . . **ix**

**Preface** . . . . . **xi**

**Xin-Chen Hong, Bao-Jie He, Jiang Liu, Jin-Da Qi, Guangyu Wang and Shi Cheng**
Biophilic Cities and Communities: Towards Natural Resources, Environmental and Social Sustainability
Reprinted from: *Sustainability* **2025**, *17*, 1881, https://doi.org/10.3390/su17051881 . . . . . **1**

**Shan Dai, Wenfeng Bai and Jing Xiao**
Balancing Environmental Impact and Practicality: A Case Study on the Cement-Stabilized Rammed Earth Construction in Southeast Rural China
Reprinted from: *Sustainability* **2024**, *16*, 8731, https://doi.org/10.3390/su16208731 . . . . . **7**

**Liupeng Chen, Yiting Wang, Yingzheng Yan, Ziwei Zhou, Bangsheng Xie and Xiaodong You**
Coupling and Coordination Development, Spatiotemporal Evolution, and Driving Factors of China's Digital Countryside and Inclusive Green Growth in Rural Areas
Reprinted from: *Sustainability* **2024**, *16*, 5583, https://doi.org/10.3390/su16135583 . . . . . **25**

**Xiaohan Zhang, Yuhao Fang, Guanting Zhang and Shi Cheng**
Exploring the Long-Term Changes in Visual Attributes of Urban Green Spaces Using Point Clouds
Reprinted from: *Land* **2024**, *13*, 884, https://doi.org/10.3390/land13060884 . . . . . **56**

**Shi Cheng, Dunsong Zhang, Yijing Wang and Xiaohan Zhang**
Exploring the Relationships between Mini Urban Green Space Layout and Human Activity
Reprinted from: *Land* **2024**, *13*, 871, https://doi.org/10.3390/land13060871 . . . . . **70**

**Yuanjing Wu, Wei Zhou, Huimin Zhang, Qunyue Liu, Zhao Yan and Siren Lan**
Relationships between Green Space Perceptions, Green Space Use, and the Multidimensional Health of Older People: A Case Study of Fuzhou, China
Reprinted from: *Buildings* **2024**, *14*, 1544, https://doi.org/10.3390/buildings14061544 . . . . . **94**

**Tian Dong, Churan Feng, Bangguo Yue and Zhengdong Zhang**
An Evaluation Model of Urban Green Space Based on Residents' Physical Activity
Reprinted from: *Sustainability* **2024**, *16*, 4220, https://doi.org/10.3390/su16104220 . . . . . **113**

**Yuxiang Lan, Yuanyang Tang, Zhanhua Liu, Xiong Yao, Zhipeng Zhu, Fan Liu, et al.**
Combined Effects of the Visual–Acoustic Environment on Public Response in Urban Forests
Reprinted from: *Forests* **2024**, *15*, 858, https://doi.org/10.3390/f15050858 . . . . . **139**

**Jing Zhang, Liwen Liu, Jianwu Wang, Dubing Dong, Ting Jiang, Jian Chen and Yuan Ren**
Exploring the Relationship between the Sentiments of Young People and Urban Green Space by Using a Check-In Microblog
Reprinted from: *Forests* **2024**, *15*, 796, https://doi.org/10.3390/f15050796 . . . . . **170**

**Carlos Ernesto Grande-Ayala**
An Assessment of Accessibility from a Socially Sustainable Urban Mobility Approach in Mass Transit Projects: Contributions from the Northern Central American Triangle
Reprinted from: *Sustainability* **2024**, *16*, 3766, https://doi.org/10.3390/su16093766 . . . . . **186**

**Yiwen Liu, Junjie Zhang, Chunlu Liu and Yang Yang**
A Review of Attention Restoration Theory: Implications for Designing Restorative Environments
Reprinted from: *Sustainability* **2024**, *16*, 3639, https://doi.org/10.3390/su16093639 . . . . . **205**

**Jinjiang Zhang, Wenyu Zhou, Haitao Lian and Ranran Hu**
Research on Optimization Strategy of Commercial Street Spatial Vitality Based on Pedestrian Trajectories
Reprinted from: *Buildings* **2024**, *14*, 1240, https://doi.org/10.3390/buildings14051240 . . . . . **223**

**Chenxi Li, Qiao Liu, Zhihong Zong and Yingying Fang**
Rural Environmental Quality Evaluation Indicator System: Application in Shangluo City, Shaanxi Province
Reprinted from: *Sustainability* **2024**, *16*, 3198, https://doi.org/10.3390/su16083198 . . . . . **244**

**Saixin Cao, Chen Song, Siwei Jiang, Hao Luo, Ping Zhang, Yinghui Huang, et al.**
Effects of Urban Greenway Environmental Types and Landscape Characteristics on Physical and Mental Health Restoration
Reprinted from: *Forests* **2024**, *15*, 679, https://doi.org/10.3390/f15040679 . . . . . **260**

**Xiangyu Fu and Yajing Liu**
Ecological Vulnerability Assessment and Spatiotemporal Characteristics Analysis of Urban Green-Space Systems in Beijing–Tianjin–Hebei Region
Reprinted from: *Sustainability* **2024**, *16*, 2289, https://doi.org/10.3390/su16062289 . . . . . **279**

**Liang Zhao, Yijie Zhang, Yiting Li, Zichao Feng and Yuetao Wang**
Correlations of Spatial Form Characteristics on Wind–Thermal Environment in Hill-Neighboring Blocks
Reprinted from: *Sustainability* **2024**, *16*, 2203, https://doi.org/10.3390/su16052203 . . . . . **302**

**Jinyan Liu, Junyi Li, Daoyuan Chen, Linye Guo, Guochang Ding and Jianwen Dong**
Differential Analysis of Island Mountain Plant Community Characteristics: Ecological Sensitivity Perspectives
Reprinted from: *Sustainability* **2024**, *16*, 1988, https://doi.org/10.3390/su16051988 . . . . . **324**

**Camilo Alberto Torres Parra, Yelinca Nalena Saldeño Madero, Mauricio González Méndez, Isidoro Fasolino, Noé Villegas Flores, Michele Grimaldi, et al.**
Evaluation of the Impact of Informal Settlements on the Physical and Mental Health of Residents—Case Study Santa Marta—Bogotá, Colombia
Reprinted from: *Sustainability* **2024**, *16*, 1964, https://doi.org/10.3390/su16051964 . . . . . **349**

**Yaxin Chen, Chuanchun Hong, Yifan Yang, Jiaxin Li, Yu Wang, Tianyu Zheng, et al.**
Mining Social Media Data to Capture Urban Park Visitors' Perception of Cultural Ecosystem Services and Landscape Factors
Reprinted from: *Forests* **2024**, *15*, 213, https://doi.org/10.3390/f15010213 . . . . . **371**

**Chen Yan, Xiangwu Cai, Yuping Wu, Xuehong Tang, Yuxuan Zhou, Qin Yang, et al.**
How Do Urban Waterfront Landscape Characteristics Influence People's Emotional Benefits? Mediating Effects of Water-Friendly Environmental Preferences
Reprinted from: *Forests* **2024**, *15*, 25, https://doi.org/10.3390/f15010025 . . . . . **393**

**Na Yao, Chenxi Gu, Jinda Qi, Shigang Shen, Bo Nan and Hongjie Wang**
Protecting Rural Large Old Trees with Multi-Scale Strategies: Integrating Spatial Analysis and the Contingent Valuation Method (CVM) for Socio-Cultural Value Assessment
Reprinted from: *Forests* **2024**, *15*, 18, https://doi.org/10.3390/f15010018 . . . . . **409**

**Tianyuan Zhu, Shuming Zhang, Yubo Wang, Cuiping Wang and Haowei Wang**
Integrated Assessment and Restoration Pathways for Holistic Ecosystem Health in Anxi County, China
Reprinted from: *Sustainability* **2023**, *15*, 15932, https://doi.org/10.3390/su152215932 . . . . . **433**

**Jing Xie, Shixian Luo, Katsunori Furuya, Huixin Wang, Jiao Zhang, Qian Wang, et al.**
The Restorative Potential of Green Cultural Heritage: Exploring Cultural Ecosystem Services' Impact on Stress Reduction and Attention Restoration
Reprinted from: *Forests* **2023**, *14*, 2191, https://doi.org/10.3390/f14112191 . . . . . **455**

**Yan Han and Yuehui Liang**
Scientific Knowledge Map Study of Therapeutic Landscapes and Community Open Spaces: Visual Analysis with CiteSpace
Reprinted from: *Sustainability* **2023**, *15*, 15066, https://doi.org/10.3390/su152015066 . . . . . **476**

**Dongxu Zhang, Xuyang Shan, Xinyi Zhang, Hao Chen and Yingsheng Zheng**
Spatial Feature Analysis of the Beijing Forbidden City and the Shenyang Imperial Palace Based on Space Syntax
Reprinted from: *Buildings* **2023**, *13*, 2615, https://doi.org/10.3390/buildings13102615 . . . . . **495**

**Xin-Chen Hong, Shi Cheng, Jiang Liu, Lian-Huan Guo, Emily Dang, Jia-Bing Wang and Yuning Cheng**
How Should Soundscape Optimization from Perceived Soundscape Elements in Urban Forests by the Riverside Be Performed?
Reprinted from: *Land* **2023**, *12*, 1929, https://doi.org/10.3390/land12101929 . . . . . **511**

**Shixian Luo, Jing Xie, Huixin Wang, Qian Wang, Jie Chen, Zhenglun Yang and Katsunori Furuya**
Natural Dose of Blue Restoration: A Field Experiment on Mental Restoration of Urban Blue Spaces
Reprinted from: *Land* **2023**, *12*, 1834, https://doi.org/10.3390/land12101834 . . . . . **524**

**Chongxiao Wang, Jiahui Zou, Xinyuan Fang, Shuolei Chen and Hao Wang**
Using Social Media and Multi-Source Geospatial Data for Quantifying and Understanding Visitor's Preferences in Rural Forest Scenes: A Case Study from Nanjing
Reprinted from: *Forests* **2023**, *14*, 1932, https://doi.org/10.3390/f14101932 . . . . . **547**

**Pegah Hajibeigi, Mahdieh Pazhouhanfar, Patrik Grahn and Hasan Nazif**
Enhancing Citizens' Perceived Restoration Potential of Green Facades through Specific Architectural Attributes
Reprinted from: *Buildings* **2023**, *13*, 2356, https://doi.org/10.3390/buildings13092356 . . . . . **569**

**Ye Chen, Ziyi Chen, Shumeng Lin, Xiaoqian Lin, Shuting Li, Taoyu Li and Jianwen Dong**
Thermal–Acoustic Interaction Impacts on Crowd Behaviors in an Urban Park
Reprinted from: *Forests* **2023**, *14*, 1758, https://doi.org/10.3390/f14091758 . . . . . **590**

**Yuxiang Lan and Qunyue Liu**
The Restorative and Contingent Value of Biophilic Indoor Environments in Healthcare Settings
Reprinted from: *Sustainability* **2023**, *15*, 11676, https://doi.org/10.3390/su151511676 . . . . . **610**

**Chenming Zhang, Bei He, Wei Li and Chunyang Guo**
Spatial Distribution and Accessibility Evaluation of National Water Parks in China
Reprinted from: *Sustainability* **2023**, *15*, 11621, https://doi.org/10.3390/su151511621 . . . . . **625**

**Shi-Ying Li, Zhu Chen, Lian-Huan Guo, Fangbing Hu, Yi-Jun Huang, Dan-Cheng Wu, et al.**
How Do Spatial Forms Influence Psychophysical Drivers in a Campus City Community Life Circle?
Reprinted from: *Sustainability* **2023**, *15*, 10014, https://doi.org/10.3390/su151310014 . . . . . **642**

**Ye Chen, Fan Liu, Xinya Lin, Jing Liu, Ziyi Chen, Kailong Shi, et al.**
Combined Effects of the Thermal-Acoustic Environment on Subjective Evaluations in Urban Park Based on Sensory-Walking
Reprinted from: *Forests* **2023**, *14*, 1161, https://doi.org/10.3390/f14061161 . . . . . **661**

**Linjia Wu, Shixian Luo, Di Li, Qibing Chen, Jingting Li and Jiacai Wen**
Effects of Deciduous Forests on Adolescent Emotional Health in Urban Areas: An Example from the Autumn Ginkgo Forest in Chengdu
Reprinted from: *Forests* **2023**, *14*, 1099, https://doi.org/10.3390/f14061099 . . . . . **682**

**Ghulam Qadir, Niranjika Wijesooriya, Arianna Brambilla and Fernando Alonso-Marroquin**
Improving the Indoor Environment through an Indoor Green Curtain System
Reprinted from: *Buildings* **2023**, *13*, 1307, https://doi.org/10.3390/buildings13051307 . . . . . **698**

**Yan Ma and Wei Xu**
How Does the Intelligent Monitoring System Influence the Sense of Security of the Elderly in Home Care? A Case Study of the Hubin Community in Ningde City
Reprinted from: *Buildings* **2023**, *13*, 1255, https://doi.org/10.3390/buildings13051255 . . . . . **718**

**Qian Yan, Shixian Luo and Jiayi Jiang**
Urban Residents' Preferred Walking Street Setting and Environmental Factors: The Case of Chengdu City
Reprinted from: *Buildings* **2023**, *13*, 1199, https://doi.org/10.3390/buildings13051199 . . . . . **734**

# About the Editors

**Xin-Chen Hong**

Dr. Xin-Chen Hong is an Associate Professor of the School of Architecture and Urban-Rural Planning at Fuzhou University, China. He holds a Ph.D. and a Master's in Landscape Architecture from Fujian Agriculture and Forestry University (including a visiting process at the University of British Columbia, Canada). He was a postdoctoral fellow at the School of Architecture at Southeast University, China. Dr. Hong's research interests are in the areas of social sensing and computational social science. His recent projects have been projects at the National Natural Science Foundation of China (NSFC) and the Key Program of Ministry of Natural Resources of China. Dr. Hong has published more than 80 articles in peer-reviewed scientific journals, such as *Sustainable Cities and Society*, *Humanities & Social Sciences Communications*, *Urban Forestry & Urban Greening*, *Building & Environment*, etc. His publications include several ESI High Cited Papers. He serves as an Associate Editor of *Frontiers in Forests and Global Change*, an Executive Editor of *Landscape Architecture Frontiers*, and a Topical Advisory Panel Member of *Forests*.

**Baojie He**

Dr. Baojie He is a (Full) Professor at the School of Architecture and Urban Planning at Chongqing University, China. He is also the director of the Centre for Climate-Resilient and Low-Carbon Cities at Chongqing University (China), Adjunct Associate Professor at University of Queensland (Australia), and Honorary Research Fellow at Hiroshima University (Japan). Prior to Chongqing University, Prof. He worked with the School of Built Environment at the University of New South Wales (UNSW Sydney), Australia. Prof. He's research focuses on Heat-Resilient Urban Planning and Design and achieving a Net-Zero carbon Built Environment. Prof. He has served as Associate Editor, Subject Editor, Editorial Board Member, and Conference Chair for many internationally renowned journals and conferences. In addition, Prof. He has been on the global list of Highly Cited Scientists (Clarivate Analytics) from 2022 onwards, and was on the Highly Cited Researchers list in China in 2024. Prof. He won the Sustainable Young Scientist Award in 2022 and the Green Talent Award (Germany) in 2021. Prof. He has been on the list of World Top 2% scientists from 2020 onwards.

**Jiang Liu**

Dr. Jiang Liu received his Ph.D. in Landscape Planning and Design at the University of Rostock in Germany in 2014. He is now a Full Professor in the Department of Landscape Architecture at the School of Architecture and Urban-Rural Planning at Fuzhou University, China. With over ten years of research experience in the soundscape field, his research focuses on the relationship between soundscapes and landscapes in different contexts, revealing the fundamental mechanism of interactions between people and the physical as well as the perceptual forms of soundscape and landscape. He has published over 50 journal publications in high-quality peer-reviewed journals, such as *Landscape and Urban Planning*, *Building and Environment*, *Urban Forestry and Urban Greening*, and *Science of the Total Environment*. He is also the director of the Environmental Psychology and Health Innovation Research Team, and vice head and co-founder of the "Key Lab of Digital Technology in Simulation and Prediction of Territorial Space" at Fuzhou University.

**Jinda Qi**

Jinda Qi holds a PhD in Built Environment from the University of New South Wales, Sydney. He has extensive work experience in both academic and industry settings across different countries, such as Australia, China, New Zealand, and Singapore. His work is highly practical, having led to collaborations with governments and industry leaders, such as the National Park Board of Singapore. He is (co-)author of several book chapters and over 30 publications in prestigious journals. He has also taken on academic roles such as PI and Co-PI for funded projects; grant reviewer for national funding, international design competition panels, and editorial boards; and guest editor of several journals.

**Guangyu Wang**

Dr. Guangyu Wang is an Associate Dean and Professor of the Faculty of Forestry at the University of British Columbia, and Director of UBC's Multidisciplinary Institute of Natural Therapy (MINT) and National Park Research Centre. He has worked intensively in national parks, recreation management, and ecotourism development in the USA, Canada, and China. He has extensive experience in protected area research and project leadership, while successfully managing CAD 4 million in research projects over the last ten years. He has completed several research projects on forest therapy and its contribution to both social and environmental wellness. Currently, his MINT team is mainly focused on the effectiveness of forest soundscapes, lightscapes, and viewscapes in improving human health and well-being. He works very closely with the Forest Therapy Hub, ANFT, Korea Forest Welfare Institute, China Forest Therapy Committee, BC Cancer Research Center, and the UBC School of Medicine. He is the author of numerous books, chapters, technical reports, and scientific papers, including around 100 peer-reviewed international journals. He serves as an Associate Editor of *Journals of Forestry Research*, *Frontier of Ecology and Evolution*, *Forests*, and many others, and as Director of the Asia Pacific Forestry Education Coordination Mechanism.

**Shi Cheng**

Dr. Shi Cheng obtained his Ph.D. in Architectural Design and Theory from Southeast University in 2020. Currently, he holds the position of Associate Researcher at the School of Architecture, Southeast University, China, and concurrently serves as a Youth Member of the National Landscape Committee under the esteemed Chinese Society of Landscape Architecture. Possessing more than five years of extensive research experience in the landscape field, Dr. Cheng specializes in exploring the relationship between crowd visual perception and landscapes through the application of various digital landscape technologies, ultimately aiming to inform and enhance urban design practices.

His academic contributions are numerous, with over 30 publications in high-caliber, peer-reviewed journals such as *Land*, *Chinese Landscape Architecture*, *Landscape Architecture*, and *Landscape Research*. Over the past five years, Dr. Cheng has spearheaded five provincial or ministerial-level research projects, including those generously funded by the NSFC and China Postdoctoral Science Foundation Special Funding. Furthermore, his accomplishments have been recognized through the receipt of more than 10 provincial or ministerial-level honors, notably, the Huaxia Construction Science and Technology Award and the National Outstanding Engineering Survey and Design Award.

# Preface

Recent years have seen increased interest in biophilic cities and communities. Biophilic design is predicated on a design philosophy that encourages the use of natural and sustainable systems to enhance the built environment at multiple scales. Currently, and with increasing frequency, a significant number of biophilic programs, policies, and initiatives are being developed in many cities around the world, facilitating natural resource conservation and environmental and social sustainability in the built environment. These trends demonstrate that biophilic perspectives as applied in cities and communities merit further exploration. Nevertheless, enhancing the built environment in order to create biophilic cities and communities is challenging.

We are honored to have edited this Topic and thank all the authors and reviewers for their excellent work and unyielding support. Further, our appreciation goes out to all the editorial teams of the participating journals for their dedication and professional editing. We also sincerely appreciate contributions from our colleagues at other institutes and corporations who collaborated on this project. Much of the research presented as part of this Topic was funded by the National Natural Science Foundation of China (No. 52208052, 52378049) and the Fujian Natural Science Foundation, China (No. 2023J05108).

Biophilic design has opened up entirely new avenues of research in the field of landscape and urban planning; however, wide application of these ideas still requires much research. As we discover and refine multi-disciplinary techniques and strengthen collaboration between academics and industrialists across the world, we will continue to pursue the full potential of biophilic cities and communities to better optimize the urban environment.

**Xin-Chen Hong, Baojie He, Jiang Liu, Jinda Qi, Guangyu Wang, and Shi Cheng**
*Topic Editors*

sustainability

MDPI

*Editorial*

# Biophilic Cities and Communities: Towards Natural Resources, Environmental and Social Sustainability

**Xin-Chen Hong [1,2,3], Bao-Jie He [4], Jiang Liu [1,*], Jin-Da Qi [5], Guangyu Wang [2,*] and Shi Cheng [3]**

[1] School of Architecture and Urban-Rural Planning, Fuzhou University, Fuzhou 350108, China; xch.hung@outlook.com
[2] Faculty of Forestry, University of British Columbia, Vancouver, BC V6T 1Z4, Canada
[3] School of Architecture, Southeast University, Nanjing 210018, China; 101300063@seu.edu.cn
[4] School of Architecture and Urban Planning, Chongqing University, Chongqing 400045, China; cces2022@cqu.edu.cn
[5] Department of Architecture, National University of Singapore, 4 Architecture Drive, Singapore 117566, Singapore; jindaqi@nus.edu.sg
* Correspondence: jiang.liu@fzu.edu.cn (J.L.); guangyu.wang@ubc.ca (G.W.)

## 1. Introduction

Biophilic design represents a design philosophy that advocates for the integration of natural and sustainable systems to enhance the built environment across various scales (e.g., the building, site, city, and regional levels) [1]. In recent years, an increasing number of biophilic programs, policies, and initiatives have been implemented in numerous cities, promoting the conservation of natural resources, as well as environmental and social sustainability within the built environment [2]. This growing trend underscores the profound implications of biophilic perspectives for cities and communities, warranting further investigation. Nevertheless, enhancing the physical environment of cities to foster biophilic cities and communities remains a significant challenge [3]. Thus, we edited a topic titled "Biophilic Cities and Communities: Towards Natural Resources, Environmental and Social Sustainability" (https://www.mdpi.com/topics/KX5WREG227 (accessed on 27 February 2023)).

This topic contains and suggests the roles of biophilic cities and communities, with contributing journals including *Buildings*, *Forests*, *Land*, *Remote Sensing*, *Smart Cities*, and *Sustainability*. It comprises thirty-seven papers addressing biophilic-related studies on natural resources, as well as environmental and social sustainability, with contributions from Asia, Europe, and America. This topic encompasses three primary research fields: (1) biophilic urbanism and processes, which emphasize topics such as land use/cover change, spatiotemporal trends, geodesign, bioclimatic design, and sustainable urban–rural planning; (2) natural resources conservation and management, which focuses on topics such as urban ecosystems, ecological patterns and processes, environmental education and policies, forest management, and nature-based solutions; and (3) computational social science and human behavior, which investigates topics such as multi-sensory interaction experiences, social and historical sensing, mental health and well-being, big data, and cognitive computing.

## 2. Summary of Articles Included in the Topic

Biophilic urbanism and processes play a significant role in fostering environmental sustainability within biophilic cities and communities. In the context of smart cities and communities, various technologies have been applied to urban open spaces and building

Received: 26 January 2025
Revised: 15 February 2025
Accepted: 21 February 2025
Published: 22 February 2025

**Citation:** Hong, X.-C.; He, B.-J.; Liu, J.; Qi, J.-D.; Wang, G.; Cheng, S. Biophilic Cities and Communities: Towards Natural Resources, Environmental and Social Sustainability. *Sustainability* **2025**, *17*, 1881. https://doi.org/10.3390/su17051881

**Copyright:** © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

interiors, including intelligent monitoring systems for the elderly [4], urban physical environment monitoring, and semantic segmentation hybrid models. In the realm of sustainable urban–rural planning, key drivers have been identified for socially sustainable urban mobility [5], digital countryside development, informal settlements [6], and hill-neighboring blocks. In the assessment of the built environment, the natural dose of blue elements plays a crucial role in the indoor environment, human activity, and mental restoration [7–9]. Moreover, one study highlights the balance between environmental impacts and practical considerations in cement-stabilized rammed earth construction.

Natural resources conservation and management play a pivotal role in promoting the sustainability of natural resources within biophilic cities and communities. Regarding Nature-Based Solutions (NBS), the characteristics of island mountain plant communities provide a scientific foundation for island ecological restoration, with similar applications extendable to mountainous and riverside areas [10]. In the context of urban ecosystems, cross-scale driving factors exhibit both shared and distinct characteristics, as reflected in ecosystem services, ecological vulnerability, and biodiversity. With respect to green sites and regions, social media and multi-source geospatial data play a crucial role in analyzing visitor preferences and accessibility [11].

Computational social science and human behavior play a critical role in advancing social sustainability within biophilic cities and communities. With regard to multi-sensory interaction experiences, the sound, light, heat, and smell of urban and rural environments significantly influence how people perceive and evaluate them, including in contexts such as water environments and green spaces [12]. Concerning public health and green exercise, biophilic design makes a notable contribution to promoting public health in both outdoor and indoor spaces [13]. Moreover, this contribution also facilitates the advancement of economic and cultural sustainability [14]. With respect to mental health and well-being, the audiovisual functions of urban blue-green spaces have garnered significant public attention, encompassing elements such as urban parks, urban greenways [6], urban waterfronts [15,16], and other forested areas [17,18]. In the domain of big data and cognitive computing, WiFi data and social media provide critical support for the development of optimization strategies within the built environment.

## 3. The Researchers' Perspectives on Biophilic Cities and Communities

To collect the perspectives of contributors to this topic, following the completion of their research, we randomly selected seven contributors from the published articles to respond to the following open-ended question: "What are the current priorities and challenges for Biophilic Cities and Communities?". The contributors were asked to provide concise comments, typically ranging from 120 to 180 words. The complete responses from the contributors, arranged alphabetically by their family name initials, are presented below.

### *3.1. Interviewee 1*

A key priority for biophilic cities could be the integration of nature into urban environments to increase exposure to natural elements, thereby enhancing human well-being. Urban green spaces in close proximity to residential areas, particularly mini urban green spaces, play a crucial role in facilitating daily recreation and green exercise. The development of high-quality mini urban green spaces aligns closely with the objectives of biophilic cities. A significant challenge involves designing and optimizing urban green spaces to promote human activity while accommodating diverse user needs. The incorporation of behavioral attributes into the design phase is both essential and inherently complex. Investigating the associations between urban green space layouts and human activity can

inform the development of innovative, evidence-based design strategies aimed at balancing the recreational, social, and ecological functions of urban green spaces.

(Assoc. Prof. Dr. Shi Cheng—Southeast University, China)

### *3.2. Interviewee 2*

Biophilic cities and communities are attracting growing attention worldwide. In China, the integration of nature into urban design is particularly significant due to the challenges posed by rapid urbanization, environmental degradation, and air pollution. The priorities for biophilic urbanism in China could include enhancing green infrastructure, such as urban parks and green roofs, to mitigate urban heat island effects and improve air quality. A key challenge lies in balancing the demand for green spaces with the competing pressures of population density and land scarcity. Furthermore, fostering community involvement and incorporating traditional Chinese landscape elements, such as garden art and water features, could enhance the richness of biophilic designs. Additionally, stronger policy frameworks and cross-sector collaboration may be required to support long-term biophilic planning, thereby ensuring that both ecological and human health benefits are accessible to all urban residents.

(Assoc. Prof. Dr. Qunyue Liu—Fujian University of Technology, China)

### *3.3. Interviewee 3*

From my perspective, biophilic cities and communities represent an approach to urban and community planning that is grounded in nature-based solutions. Amid today's rapid urbanization, an increasing number of city dwellers are experiencing various forms of stress. As a result, the application of nature-based solutions—such as natural infrastructure, natural resources, and digital nature—has become a fundamental component of contemporary urban and community planning, aimed at alleviating stress across diverse population groups. Our research has demonstrated that natural resources, particularly green spaces, have significant positive effects on human mental health. However, empirical studies on blue spaces remain limited, and this is an area we are actively exploring.

Nonetheless, the application of such natural solutions to enhance mental health is still accompanied by several challenges. These include the difficulty of generalizing laboratory findings to real-world environments, determining the optimal "doses" of natural resources, and understanding how different population groups respond to various natural stimuli. We strongly encourage further scholarly efforts in these areas to advance the development of biophilic cities and communities.

(Assi. Prof. Dr. Shixian Luo—Southwest Jiaotong University, China)

### *3.4. Interviewee 4*

Biophilic cities and communities aim to inspire a deeper connection to nature by creating opportunities for residents to engage with natural environments and cultivate a sense of place. This concept can be recognized as a nature-based solution enabling cities and communities to address challenges such as population agglomeration, limited green space, the loss of natural heritage and place attachment, as well as biotic homogenization within urban green spaces. In this context, the promotion of biocultural diversity and natural resource conservation should be regarded as a priority. However, implementing large-scale, targeted conservation measures for natural heritage poses significant challenges under the conventional government-dominated approach. Socio-cultural value assessments of natural resources and heritage (e.g., large old trees) grounded in public perceptions can foster collaborative participation among diverse stakeholders. In turn, multi-scale conservation strategies enhance the intangible yet diverse natural values that characterize biophilic cities and communities.

(Prof. Dr. Hongjie Wang—Hebei University, China)

### *3.5. Interviewee 5*

In biophilic cities, the integration of nature into urban and landscape design serves to enhance human well-being, strengthen resilience, and support the preservation of cultural heritage. Cultural heritage, as a vital component of communities, fosters profound connections between people, nature, and history. Through the integration of natural and cultural elements, such as historic green spaces and traditional ecological knowledge, biophilic design reinforces local identity while advancing sustainable development. Nevertheless, achieving a balance between urbanization and cultural heritage conservation remains a significant challenge, particularly in rapidly expanding cities. By fostering community engagement and utilizing innovative design approaches, biophilic cities have the potential to harmonize nature, culture, and modern life, thereby contributing to resilient urban futures.

(Dr. Jing Xie—Chiba University, Japan)

### *3.6. Interviewee 6*

A central priority in contemporary urban planning is to cultivate a stronger connection between residents and nature, especially in densely populated areas. Urban planners should emphasize the design of spaces that support both mental and physical well-being by embedding biophilic elements, seamlessly integrating nature into urban environments to elevate the quality of everyday urban life. In this context, public spaces—such as streets and squares—should act as transitional zones that bridge the divide between "gray" urban infrastructure and "green" natural elements, facilitating seamless interactions between the two. Such integration is essential for mitigating the psychological and physical stress commonly associated with urban living.

A major challenge lies in striking a balance between the pressures of urban density and the necessity of maintaining adequate green spaces. It is crucial to strategically plan functional zones in ways that optimize the spatial relationships between built structures and green areas. As cities continue to expand, preserving and integrating green spaces within urban development processes not only enhances urban livability, but also fosters long-term ecological sustainability.

(Dr. Qian Yan—Seoul National University, Korea)

### *3.7. Interviewee 7*

Exploration of human–environment interactions and strategies to create an attractive built environment to encourage people to be close to nature could be one of the topics in biophilic cities and communities. The link between urban green space features and human health and well-being has been increasingly emphasized as more studies on human perception and preference for the built environment and green space have been conducted. However, maintaining urban green spaces in a static spatial form through extensive pruning and other high-intensity maintenance practices to meet people's preferences is both costly and detrimental to the ecological services provided by vegetation. Thus, it is still challenging to comprehensively consider the long-term dynamic changes in urban green spaces, including vegetation growth, urban development, and shifts in resident behavior, while efficiently utilizing limited spatial resources to meet the increasing ecological and recreational demands and sustainability.

(PhD Candidate Xiaohan Zhang—Technical University of Munich, Germany)

## 4. Concluding Remarks

We extend our sincere gratitude to the contributors of this topic for their valuable work. As emphasized by many authors in this topic, biophilic cities and communities have garnered significant attention within urban studies, reflecting their growing relevance in addressing contemporary urban challenges. We believe that biophilic cities and communities represent an important area for further exploration and discussion. In particular, the intersection of ecology and exposure science with health-related concerns has led to the progressive integration of these topics into academic discourse. To advance this field, we introduce a new topic titled "Biophilic Cities and Communities: Human-Environment Interaction and Sustainable Governance" (https://www.mdpi.com/topics/DP2IH99GRY (accessed on 25 June 2024)). This topic is designed to unite researchers working on related areas, providing a platform for the exchange of innovative findings and fostering collaboration across disciplines. Furthermore, we encourage future research to focus on the following key areas:

(i) Biophilic urbanism and processes. This area encompasses a range of topics, including smart cities and communities, land use and land cover changes, spatial-temporal trends, geodesign, urban landscape patterns, sustainable urban–rural planning, and built environment assessments. These topics are instrumental in advancing our understanding of the processes and principles underpinning biophilic urbanism.

(ii) Human–environment interaction. This field includes crucial themes, such as environmental behavior and local practices, social and historical sensing, economic and cultural sustainability, the application of big data and social computing, social equity, and sustainable governance frameworks. These perspectives provide a foundation for addressing the intricate relationships between humans and their environments.

(iii) Exposure ecology. Key areas within this field include urban and natural ecosystems, ecological patterns and processes, ecological exposure, forest management, nature-based solutions, and public health and well-being. Research in this domain is essential for understanding the ecological dimensions of urban living and their implications for human health.

**Author Contributions:** Conceptualization, X.-C.H., J.L., G.W. and S.C.; writing—original draft preparation, X.-C.H. and J.L.; writing—review and editing, B.-J.H. and J.-D.Q.; supervision, J.L. and G.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This project was supported by the National Natural Science Foundation of China (52208052, 52378049), Fujian Natural Science Foundation, China (No. 2023J05108), and the Humanities and Social Science Research Program of Ministry of Education of China (Grant No. 21YJCZH038).

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Gillis, K.; Gatersleben, B. A review of psychological literature on the health and wellbeing benefits of biophilic design. *Buildings* **2015**, *5*, 948–963. [CrossRef]
2. Lin, H.; Wang, J.B.; Zhang, X.; Hu, F.B.; Liu, J.; Hong, X.C. Historical sensing: The spatial pattern of soundscape occurrences recorded in poems between the Tang and the Qing Dynasties amid urbanization. *Humanit. Soc. Sci. Commun.* **2024**, *11*, 730. [CrossRef]
3. Toyoda, A.; Shibata, Y.; Matsuo, Y.; Terada, K.; Sugimoto, H.; Higashi, K.; Mori, H.; Ikeuchi, A.; Ito, M.; Kurokawa, K.; et al. Diversity and compositional differences of the airborne microbiome in a biophilic indoor environment. *Sci. Rep.* **2023**, *13*, 8179. [CrossRef] [PubMed]
4. Ma, Y.; Xu, W. How Does the Intelligent Monitoring System Influence the Sense of Security of the Elderly in Home Care? A Case Study of the Hubin Community in Ningde City. *Buildings* **2023**, *13*, 1255. [CrossRef]
5. Zhang, D.; Shan, X.; Zhang, X.; Chen, H.; Zheng, Y. Spatial Feature Analysis of the Beijing Forbidden City and the Shenyang Imperial Palace Based on Space Syntax. *Buildings* **2023**, *13*, 2615. [CrossRef]

6. Cao, S.; Song, C.; Jiang, S.; Luo, H.; Zhang, P.; Huang, Y.; Yu, J.; Li, K.; Li, N.; Guo, B.; et al. Effects of Urban Greenway Environmental Types and Landscape Characteristics on Physical and Mental Health Restoration. *Forests* **2024**, *15*, 679. [CrossRef]
7. Hajibeigi, P.; Pazhouhanfar, M.; Grahn, P.; Nazif, H. Enhancing Citizens' Perceived Restoration Potential of Green Facades through Specific Architectural Attributes. *Buildings* **2023**, *13*, 2356. [CrossRef]
8. Qadir, G.; Wijesooriya, N.; Brambilla, A.; Alonso-Marroquin, F. Improving the Indoor Environment through an Indoor Green Curtain System. *Buildings* **2023**, *13*, 1307. [CrossRef]
9. Yan, Q.; Luo, S.; Jiang, J. Urban Residents' Preferred Walking Street Setting and Environmental Factors: The Case of Chengdu City. *Buildings* **2023**, *13*, 1199. [CrossRef]
10. Hong, X.-C.; Cheng, S.; Liu, J.; Guo, L.-H.; Dang, E.; Wang, J.-B.; Cheng, Y. How Should Soundscape Optimization from Perceived Soundscape Elements in Urban Forests by the Riverside Be Performed? *Land* **2023**, *12*, 1929. [CrossRef]
11. Wang, C.; Zou, J.; Fang, X.; Chen, S.; Wang, H. Using Social Media and Multi-Source Geospatial Data for Quantifying and Understanding Visitor's Preferences in Rural Forest Scenes: A Case Study from Nanjing. *Forests* **2023**, *14*, 1932. [CrossRef]
12. Chen, Y.; Chen, Z.; Lin, S.; Lin, X.; Li, S.; Li, T.; Dong, J. Thermal–Acoustic Interaction Impacts on Crowd Behaviors in an Urban Park. *Forests* **2023**, *14*, 1758. [CrossRef]
13. Wu, L.; Luo, S.; Li, D.; Chen, Q.; Li, J.; Wen, J. Effects of Deciduous Forests on Adolescent Emotional Health in Urban Areas: An Example from the Autumn Ginkgo Forest in Chengdu. *Forests* **2023**, *14*, 1099. [CrossRef]
14. Yao, N.; Gu, C.; Qi, J.; Shen, S.; Nan, B.; Wang, H. Protecting Rural Large Old Trees with Multi-Scale Strategies: Integrating Spatial Analysis and the Contingent Valuation Method (CVM) for Socio-Cultural Value Assessment. *Forests* **2024**, *15*, 18. [CrossRef]
15. Yan, C.; Cai, X.; Wu, Y.; Tang, X.; Zhou, Y.; Yang, Q.; Li, F.; Lan, S.; Lin, L. How Do Urban Waterfront Landscape Characteristics Influence People's Emotional Benefits? Mediating Effects of Water-Friendly Environmental Preferences. *Forests* **2024**, *15*, 25. [CrossRef]
16. Luo, S.; Xie, J.; Wang, H.; Wang, Q.; Chen, J.; Yang, Z.; Furuya, K. Natural Dose of Blue Restoration: A Field Experiment on Mental Restoration of Urban Blue Spaces. *Land* **2023**, *12*, 1834. [CrossRef]
17. Lin, H.; Hong, X.-C.; Wen, C.; Hu, F. The historical sensing of urban forest based on the indicators of CES and landscape categories: A case of Kushan scenic area in CHINA. *Ecol. Indic.* **2024**, *166*, 112440. [CrossRef]
18. Han, Y.; Liang, Y. Scientific Knowledge Map Study of Therapeutic Landscapes and Community Open Spaces: Visual Analysis with CiteSpace. *Sustainability* **2023**, *15*, 15066. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# Balancing Environmental Impact and Practicality: A Case Study on the Cement-Stabilized Rammed Earth Construction in Southeast Rural China

**Shan Dai [1], Wenfeng Bai [2] and Jing Xiao [2,*]**

[1] School of Architecture, The Chinese University of Hong Kong, Hong Kong, China; daishan@link.cuhk.edu.hk
[2] Faculty of Architecture and City Planning, Kunming University of Science and Technology, Kunming 650032, China; baiwenfeng@ccmccf.org.hk
* Correspondence: jing@ccmccf.org.hk; Tel.: +86-139-8710-2006

**Abstract:** Construction using earth materials demonstrates ecological sustainability using locally sourced natural materials and environmentally friendly demolition methods. In this study, the environmental impact of adding cement to soil materials for rammed earth farmhouse construction in rural China was investigated and comparatively simulated using the One Click LCA database, focusing on the conflict between sustainability objectives and the practical aspects of cement addition. By analyzing how the addition of cement aligns with local construction practices and addressing the debate surrounding the inclusion of cement in rammed-earth construction, our objective is to provide insights into achieving a balance between the environmental impact and the pragmatic considerations of using cement in earthen building practices. Three local structure scenarios are evaluated via simulations: cement-stabilized rammed earth wall, fired brick wall, and a localized reinforced concrete frame structure. The quantitative environmental impacts are assessed, and the qualitative differences in adaptation, economic sustainability, and other factors are examined in the context of present-day development in rural China. The results show that the use of cement-stabilized rammed earth wall-supported structures is associated with higher embodied carbon emissions compared to structures supported by reinforced concrete frames and enclosed by brick walls; however, these emissions are lower than those for brick wall-supported structures while effectively meeting the structural requirements. In addition, the use of cement-stabilized earth for perimeter walls simplifies material management and disposal throughout the building's life cycle, and the cost-effectiveness of cement has been found to be substantially greater than that of reinforced concrete frames and brick structures, improving economic viability and social acceptability, especially among low-income communities in rural areas

**Keywords:** cement-stabilized rammed earth; rural area; software simulation; sustainable evaluation

**Citation:** Dai, S.; Bai, W.; Xiao, J. Balancing Environmental Impact and Practicality: A Case Study on the Cement-Stabilized Rammed Earth Construction in Southeast Rural China. *Sustainability* **2024**, *16*, 8731. https://doi.org/10.3390/su16208731

Academic Editors: Md. Mizanur Rahman and Paulo Santos

Received: 3 May 2024
Revised: 13 September 2024
Accepted: 9 October 2024
Published: 10 October 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Along with China's rapid economic development over the past few decades, the urbanization and hollowing out of villages in rural areas have led to a massive concentration of people in towns and cities [1], with the number of natural villages in China declining by more than 12.8% between 2006 and 2021 [2]. The rapid development of information interaction and the updating of construction technology and materials have had a significant impact on traditional human construction methods, such as rammed earth, and large-scale self-demolition and self-built construction have occurred in rural areas of China [3], where rural residents have begun to emulate the standards of urban living, replacing the original earth and wood structures with energy-intensive construction materials such as reinforced concrete, masonry, and steel. People left behind are not able to uphold the maintenance of traditional buildings, and the loss of powerful and skillful labor has significantly challenged the inheritance of local construction traditions [4,5]. Building sustainable development is

an urgent but inevitable goal that needs to be achieved globally. Current rural development in China is facing the following multiple challenges [6–8]:

- Simultaneously achieving twin rural revitalization and dual carbon emission reduction policy objectives.
- The loss of labor fundamentally hampers village behavior associated with human activity.
- China is going through a transition phase from poverty eradication to rural revitalization, and the level of infrastructure development in rural areas is relatively lagging, posing a risk of returning to poverty.
- Industrialized materials and technologies impact traditional construction techniques.
- Increased frequency of unpredictable weather extremes and natural disasters.
- The increased use of multiple channels to obtain information and resources without improving discernment. Although the population has decreased, resource consumption and carbon emissions have increased.

Because of the above challenges, the core objectives of housing in rural areas include the following: to improve the quality of housing, to reconfigure rural community relations through public gathering activities such as housing construction in villages while ensuring affordability, to reduce the use of energy-intensive materials and equipment, to encourage the active participation of elderly people in villages to work and be remunerated in phases while housing construction activities are carried out, and to increase the number of people in the villages who are left behind. One of the first issues to be addressed is how to solve the current housing demand problem with the lowest cost and lowest environmental impact technology to achieve comfortable housing conditions.

Rammed earth construction is the most widely used technique in the world, which could be constructed to be load-bearing structures if accompanied by the appropriate density and additions [9]. The practical project in Yunnan province has proved that the dry compressive strength of a rammed earth block in lab conditions can be improved from 1 Mpa to 3 Mpa on average by re-proportioning sand and gravel and adding about 3% cement to the soil with a clayey soil extracted from the site [10]. Shaking table experiments have also proved that a load-bearing building with appropriate proportion and binders of earth wall can satisfy the requirements of eight-degree seismic fortification [11].

Of course, the stability of rammed earth construction has always been a controversial practice, mainly in Australia [12]. The prototype was conducted based on the site where the soil is too sandy or clayey, which should be appropriate to add stabilizers to improve the durability of the earth wall and to cope with the dry compressive strength, to reduce the quality of the soil itself, which could have an either positive or negative effect on the limitations of the construction of rammed earth. On the other hand, scholars of rammed earth construction, mainly in Europe, believe that the addition of chemical stabilizers to the soil, as a natural material that can be recycled and reused, will destroy the properties of the soil itself, which will make it more difficult to be dismantled and reused, with a lower value, and will increase the load on the environment [13]; when the 'affordable' nature of rammed earth construction conflicts with its 'green' attributes, the balance of factors to be considered determines the final construction technology program.

A development strategy of rammed earth buildings that corresponds to the above challenges should be designed to deal with different local contexts, such as capable resources, the workmanship of local laborers, climate and geographical situations, cultural beliefs, etc. Pelé-Peltier and Charef [14] reviewed the multiple factors that affected the use of earth material in industrial construction. Currently, for remote mountain villages in southeast China, meeting policy requirements and economic acceptability are the primary conditions for initiating the renewal of farmhouse construction. Using rammed earth as the primary building material can result in significant cost savings [15]. In addition, social elements and environmental impacts must be prioritized before renewal. Traditionally, in rural China, there is a human or clan bond, and in the past, houses were constructed based on the village residents' mutual help [16]. With population loss and the gradual

weakening of community relations in villages, public affairs in villages have gradually transformed from clan management to a market economy. However, the people's influence is still apparent. Due to limited transportation in rural China, especially in mountainous areas, and the current low level of mechanization in rural house building, the construction of most houses is still labor-intensive. By organizing labor-intensive activities such as rammed earth construction, surplus laborers in villages, including the elderly and women, are encouraged to participate in construction work actively, gradually refining the cooperative model and re-establishing rural community relations during the project. This is the primary significance of this case study.

## 2. Research Progress of Rammed Earth

We are seeking solutions from nature, such as the recap of the implementation of biomass materials to replace energy-intensive components [17]. Engineers have been constructing earthen buildings since the 1950s, which are not only capable of performing as building envelopes but also as load-bearing structures [13]. The characteristics that represent the sustainable definition of earth construction, such as locally obtained resources, renewable and recyclable materials, the excellent hydrothermal performance of mass earth walls, economically affordable construction [18], easy-to-learn construction techniques [19], etc., have been widely recognized; the widespread use of rammed earth construction is constrained by multiple factors no matter whether in developed or developing regions [14]. Rammed earth construction is the most widely adopted technique among the recognized 12 types of earthen techniques in the world [9]. It is constructed to compact a mixture of soil and water between temporary forms layer by layer. Areas such as the structure, material proportioning, construction organization, and thermal performance of rammed earth buildings have already been studied. The referred literature is listed in Table 1.

**Table 1.** Research perspectives of earthen structures.

| Literature | Research Perspectives | Content |
| --- | --- | --- |
| [9,15,20–30] | Material Properties and Construction Techniques | These studies examine earth materials' physical and mechanical properties, including their thermal mass, moisture absorption, and compressive strength. Research also focuses on traditional building techniques versus modern innovations in earth construction. |
| [23,25,31–37] | Sustainability and Environmental Impact | Many researchers have compared the sustainability of earth constructions to conventional building methods. This includes assessing the carbon footprint, energy efficiency, and potential for local material sourcing. |
| [11,38–47] | Seismic Performance | Since many earth structures are in seismically active regions, research often focuses on earthen buildings' structural integrity and behavior during earthquakes, including retrofitting methods and design modifications. |
| [48,49] | Cultural and Historical Perspectives | Earth architecture is often studied for its cultural significance, historical development, and traditional knowledge associated with earth construction, including how these practices can be preserved or revitalized. |
| [50–58] | Thermal Performance and Energy Efficiency | Investigations into how earth buildings perform thermally can reveal insights into energy savings and occupant comfort, often comparing these structures to those built with conventional materials. |
| [23–25,59–66] | Modern Applications and Innovations | Research includes integrating earth materials with modern technologies, such as prefabrication techniques, hybrid building materials, and innovative engineering solutions. |
| [67–72] | Regulatory and Policy Frameworks | Studies sometimes examine how building codes and regulations impact the use of earth as a building material, including barriers and opportunities for broader adoption in contemporary construction practices. |

**Table 1.** *Cont.*

| Literature | Research Perspectives | Content |
| --- | --- | --- |
| [15,35,62,73,74] | Socioeconomic Factors | Research may also cover the socioeconomic implications of using earth materials, particularly in developing regions where earth construction can provide affordable and accessible housing solutions. |
| [62,73,75] | Resilience and Adaptation | As climate change poses challenges, ongoing research is being conducted into how earth-based structures can be adapted or designed to withstand extreme weather conditions and contribute to community resilience. |

On a practical level, however, the study of rammed earth architecture has been ongoing for decades, and general acceptance remains low. Ben-Alon et al. [76] analyzed that the building permit is the strongest barrier for earthen buildings in the context of developed countries with well-established construction systems. However, the acceptance of earthen houses in less developed areas is also low, the main reason being that the locals think it is disgraceful to live in an earthen house [62,76,77]. Both types of impediments exist in rural China. Addressing the contradictions between quality living conditions and low environmental impact is a long-lasting research topic.

An analysis of the historical progression of earthen architecture revealed that each method of constructing with earth is a response to a specific social setting and the prevailing circumstances of that era [37,78–80]. However, in the past, most people in Asia and Africa, where most of the population is engaged in agriculture, strongly associated earthen buildings with poverty and backwardness, preferring industrialized materials such as cement and steel [31,79]. Since man began choosing industrialized materials over nature-based construction, there has been drastic resource depletion and a climate crisis. The transition to natural construction is an unavoidable trend; however, it is still primarily hindered by a lack of knowledge and restoration of the value of the modern system of nature-based construction. Thus, Heringer et al. summarize the years of practice and research on rammed earth construction and pose the central question, "Who profits?" [31]. The renowned American economist Jeremy Rifkin predicts an imminent end to wage labor in industrial production as intelligent technologies surpass the cost efficiency of human labor worldwide. Considering this transformative shift, Rifkin emphasized the need for innovative solutions to overcome the challenges posed by the decline in mass labor. Conversely, by reassessing its priorities, the construction industry promises to address the increasing demand for work and wage labor in the future [31]. The main advantage of expanding earthen construction lies in its ability to effectively meet these demands while maintaining a balance between labor, production costs, embodied energy, water consumption, and resource transportation, thus promoting equity. Despite these potential benefits, the widespread adoption of earth construction practices remains limited. Of this rammed earth, wattle and daub, cob, adobe, and compressed earth block (CEB), rammed earth construction requires the most teamwork.

Rammed earth construction projects are joint in China's east, southeast, southwest, and northwest regions. Most of them involve renovating traditional earthen buildings, such as the Fujian Tulou, terraced adobe houses in Yunan, and caves in Gansu. Building with modern technology focuses on upgrading rural homes and post-disaster reconstruction. In both situations, constructing rammed earth buildings does not provide designers or builders with adequate financial resources and response times for the precise and accurate control of architectural details. A rough type of design and construction organization is more suitable for upgrading rural households and construction during a disaster context, whether due to the lifestyle habits of rural residents or the urgency of disaster relief. Considering the limited financial resources in both areas, rammed earth construction in rural China, especially for self-built houses and disaster relief, usually involves adding cement or incorporating structural elements such as steel bars or bamboo strips to ensure safe and comfortable shelters while keeping costs manageable.

Therefore, this study hypothesizes that cement-stabilized rammed earth buildings should be environmentally superior to brick masonry and reinforced concrete frame structures, which are common in rural areas of southeastern China. A life cycle analysis (LCA) using the One-Click LCA database was conducted to assess the embedded carbon emissions of the three types of structures, cement-stabilized rammed earth, brick masonry, and reinforced concrete, and to analyze the economic performance of the three technological tools in the context of actual project records. It can provide a reference value for future housing renewal and renovation in other relatively underdeveloped areas.

## 3. Case Study

### *3.1. Comparative Simulation Study*

This study examines rural housing construction in China by taking a holistic approach to life cycle analysis. A comparative simulation analysis was carried out using the Design Builder software, Version 7.3.0.029, in conjunction with the One Click LCA database, which Bionova Ltd. (Helsinki, Finland) developed to comply with EN 15978 standard [81], to simulate the daylighting performance of standard building units and associated embodied carbon emissions. While the existing databases need to be expanded to be more relevant to the Chinese context, evaluating different construction methods for embodied energy consumption remains a valuable source of insight. This study extends the analysis of rammed earth construction with cement to encompass sociological and economic dimensions within the current Chinese development landscape and presents a case study involving the renovation of self-built rural houses in southeast China.

In this study, three standard building blocks commonly implemented in southeast rural China, with buildings of dimensions 3 × 5 × 3 m (width (W) × length (L) × height (H)), were simulated and constructed using four types of building materials: fired brick, cement-stabilized rammed earth (CSRE), concrete, and reinforcement steel bar. A foundation with a height of 200 mm, and a flat concrete roof thickness of 100 mm, and an extension of 300 mm on top of each block for puncture protection of the wall were proposed (Table 2).

**Table 2.** Parameters, quantities, and estimated material costs for the three blocks compared.

| Title 1 | Unit | Block 1 | Block 2 | Block 3 |
|---|---|---|---|---|
| Parameter | | | | |
| Load-bearing structure | | 380 mm thick fired brick wall | 350 mm thick 5% cement-stabilized rammed earth wall | 200 mm (W) × 300 mm (L) reinforced concrete frame |
| Footing | mm | 200 (H) × 380 (W) | 200 (H) × 350 (W) | 200 (H) × 200 (W) |
| Material | | | | |
| Concrete | $m^3$ | 3.60 | 3.49 | 3.62 |
| Steel bar | kg | 382 | 382 | 423 |
| Cement | kg | 720 | 1075 | 395 |
| Fired brick | kg | 23,123 | 0 | 13,224 |
| Cost [1,2] | | | | |
| Concrete | CNY/$m^3$ | 352.8 | 342.02 | 354.76 |
| Steel bar | CNY/m | 1834 | 1834 | 1905 |
| Cement | CNY/ton | 302 | 452 | 166 |
| Fired brick | CNY/piece | 3078 | 0 | 1764 |

[1] The unit price for each material refers to a project in southeast China. [2] The estimated cost of each material was calculated by considering 5% waste as indicated in practice.

Figure 1 shows the simulated annual daylight factor for the standard layout plan of the three blocks. This study aims to focus on the embodied carbon emissions of the different building materials to facilitate the frequent implementation of load-bearing structures in rural areas in southeast China. Figure 2 displays the study cases, which include a standard

bedroom floor plan, which shows a good annual daylighting factor for the accommodation, and embodied carbon benchmarking for a single block built with an envelope.

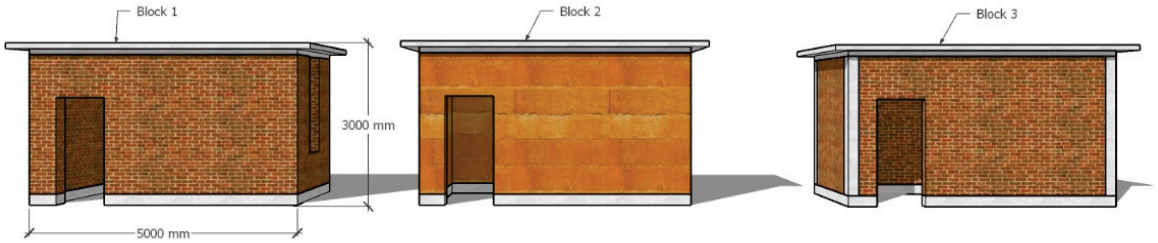



**Figure 1.** Model of the three blocks under comparison.

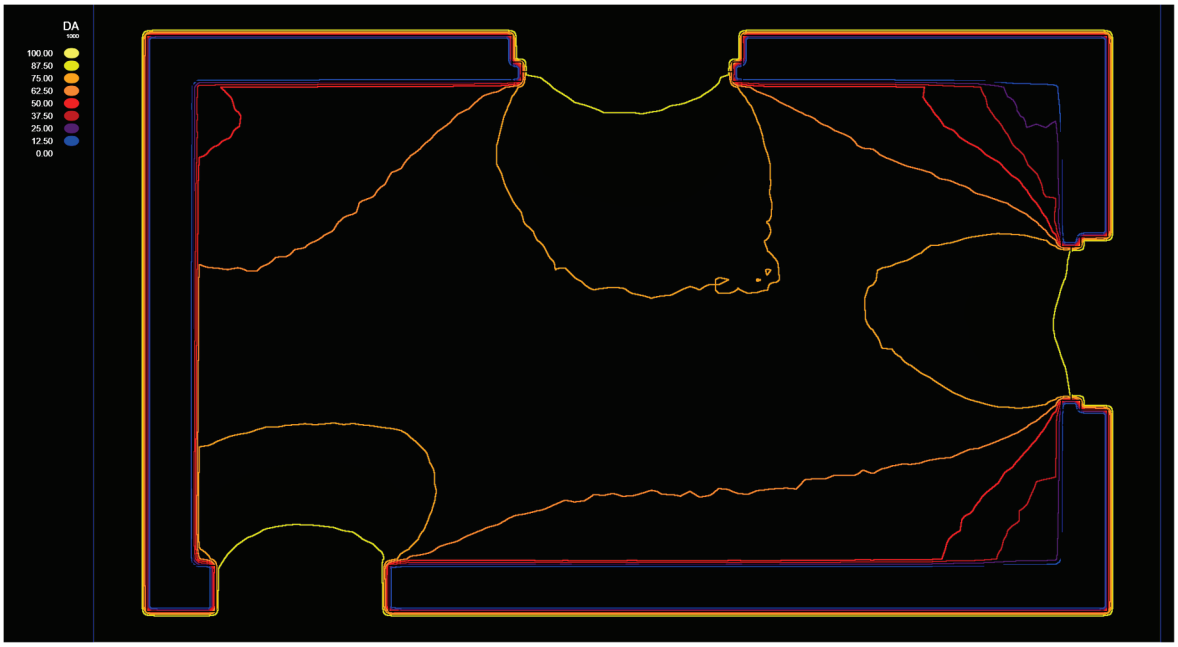



**Figure 2.** Simulated annual daylight factor for the standard layout plan of the three blocks.

To account for the specific conditions at the project location, the dependent variables in the three simulation results encompass variations in the quantities of the four primary materials based on typical local construction methods and discrepancies in the materials used for the vertical structures.

The modeling data analysis (Figure 3) indicates that among the existing construction methods for rural residential buildings in southeast China, using 380 mm thick brick walls as load-bearing elements shows the highest hidden energy consumption. This is followed by rammed earth walls reinforced with cement, with framed structures incorporating the load-bearing elements, which have the lowest hidden energy consumption.

The development of simulation software for preliminary decision-making analysis is a widely accepted method to help designers optimize the design at an early stage [82]. However, the simulation tool is always based on the data already collected to provide a platform for real-time data updating, and the collection of the regional characteristics of the parameters still has its limitations. Therefore, researchers and scholars often simulate the data with the measured data to compare and make a comprehensive judgment. Even though most of the databases of One Click LCA in this study are from European countries and do not match the actual data from rural China, it is still valuable to qualitatively assess the advantages of the three building systems, namely brick masonry, stabilized rammed earth, and framed structure, for reducing hidden energy consumption. To further substantiate the hypothesis put forward in this study regarding the sustainability of adding

cement to rammed earth buildings, a case study on renovating a rural rammed earth dwelling located in the mountainous region of southeastern China is conducted.

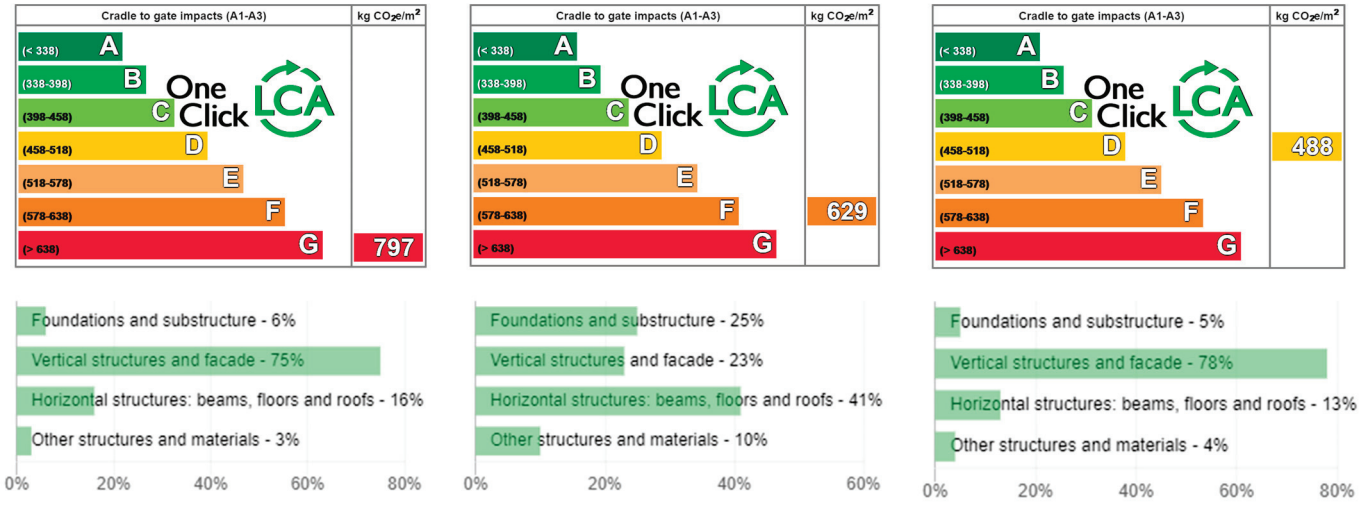



**Figure 3.** Embodied carbon benchmarking for a single block built with an envelope. (**a**) A 380 mm thick fired brick wall, (**b**) 350 mm thick rammed earth wall, and (**c**) reinforced concrete framing structure and 200 mm thick fired brick wall, which corresponds to the parameters in Table 2.

### *3.2. Project Case Study*

Existing Situation on Site

The site selected for the pilot project is in southeast China, and it is originally an ethnic Yao settlement with a hot summer and cold winter climate. The project was launched after China had fully completed its poverty eradication mission. The projects initially aimed to preserve and restore some of the vacant traditional rammed earth dwellings. The village had lost many laborers in the past due to prevailing policies and urbanization; therefore, there were less than ten permanent residents in the village at the beginning of the project, and the average age was over 60.

There were approximately 12 traditional rammed earth buildings and 5 modern brick and masonry houses; the traditional rammed earth settlement style of the village had been destroyed, as shown in Figure 4.

**Figure 4.** The image on the left shows the present-day depiction of the village before the project commenced in 2021, while the image on the right showcases the village landscape circa 2008.

The pilot project was conducted with the support of non-governmental organizations, as the permanent population of the village was very sparse. Most of them were retired elderly people. Traditional rammed earth construction is an undeniable feature of the village. The project team's investigation was conducted during the hot summer months. When surveying each of the earth buildings, it was evident that the existing earth buildings were very cool inside, but the lighting could be better. The front and back of the main halls of each earth building were ventilated, but the bedrooms on the left and right sides needed better ventilation and daylighting due to poor existing situations, as Figure 5 shows. Moreover, due to the traditional building's left–right symmetrical layout, the occupants' requirements and privacy were not overly considered. As a result, most household interviews revealed a conflict between the existing rammed earth houses and the actual use of the function, including most of the unused space on the first floor.

**Figure 5.** Interior condition of an existing rammed earth dwelling in the village.

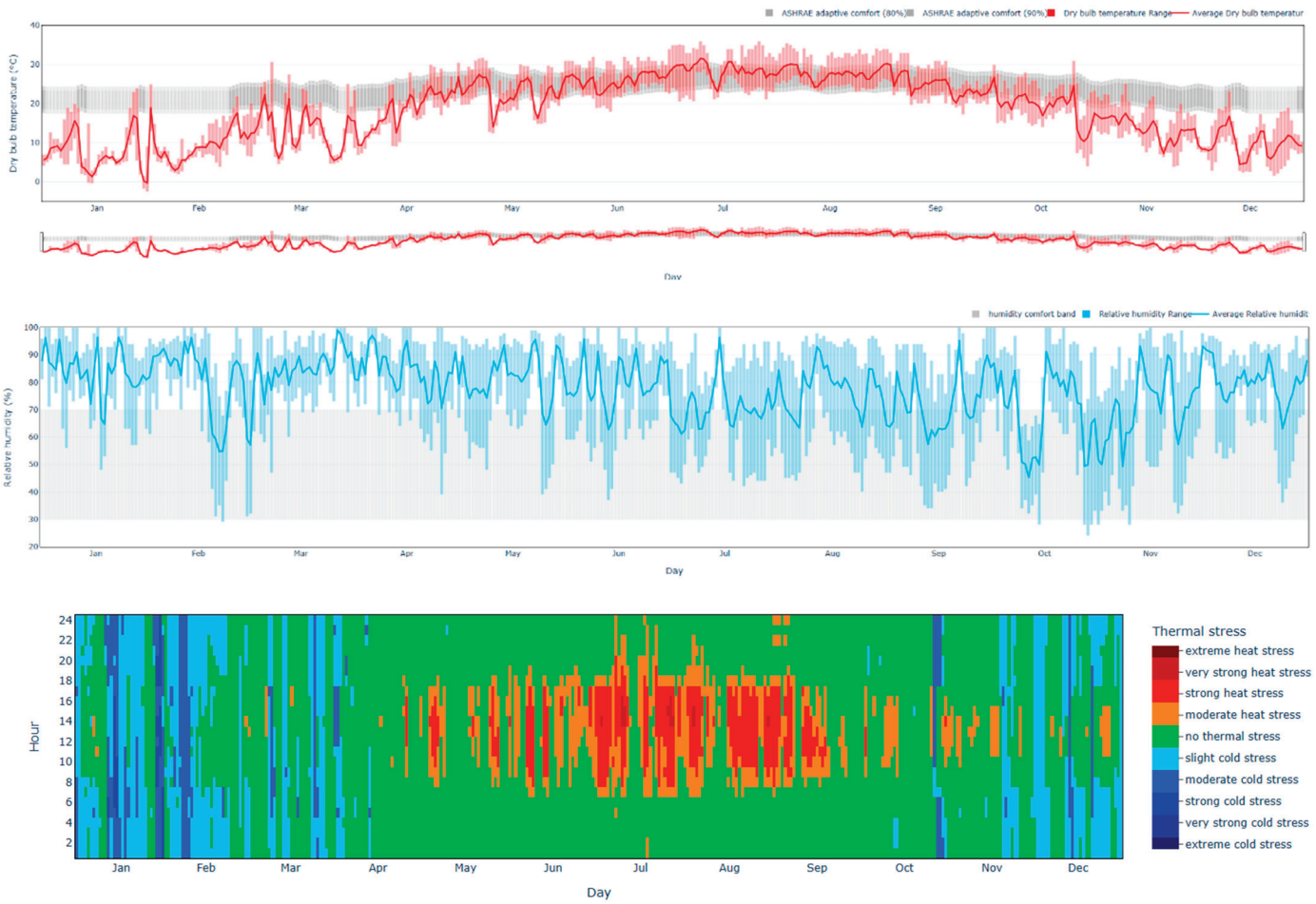
In the pilot project, some strategies were applied to investigate the feasibility and possibility in the context of the current situation, such as encouraging the elderly to participate and organize the construction of rammed earth houses in their villages to the best of their ability, using the recycled materials from existing buildings and excavated sites, proposing a cement-stabilized rammed earth technique combined with an aluminum formwork and using an electrical rammer to improve the building quality and construction efficiency.

The selected case projects have two main objectives: to help improve the housing quality and provide safe and comfortable accommodation for the village residents. Secondly, to explore step-by-step a sustainable development model that encompasses the village architecture's environmental, economic, and social dimensions. For the case selected for this study, a multi-stakeholder partnership model is proposed that involves examining the living and production habits of rural residents in the area, the types of resources available in the area, and the artisans experienced in construction. In addition, an analysis of the climatic conditions in the region revealed that it was rainy and humid throughout the year and that frequent rainfall in the region's mountainous areas is not conducive to rammed earth construction.

An analysis of meteorological data for Dao Xian County, the closest county to the site, was conducted using Berkeley's CBE tool [83,84], as illustrated in Figure 6a. In addition to the recorded outdoor temperature and humidity data for the site, the geographical location of the village was found to be consistent with the climatic patterns of cold winters and hot summers [85]. During the winter season when there is little rainfall, the average external relative humidity can exceed 85%. According to the on-site monitoring of microclimate date, as Figure 6b presents, these environmental conditions, characterized by high humidity levels and frequent rainfall [86], can pose a challenge to rammed earth construction.

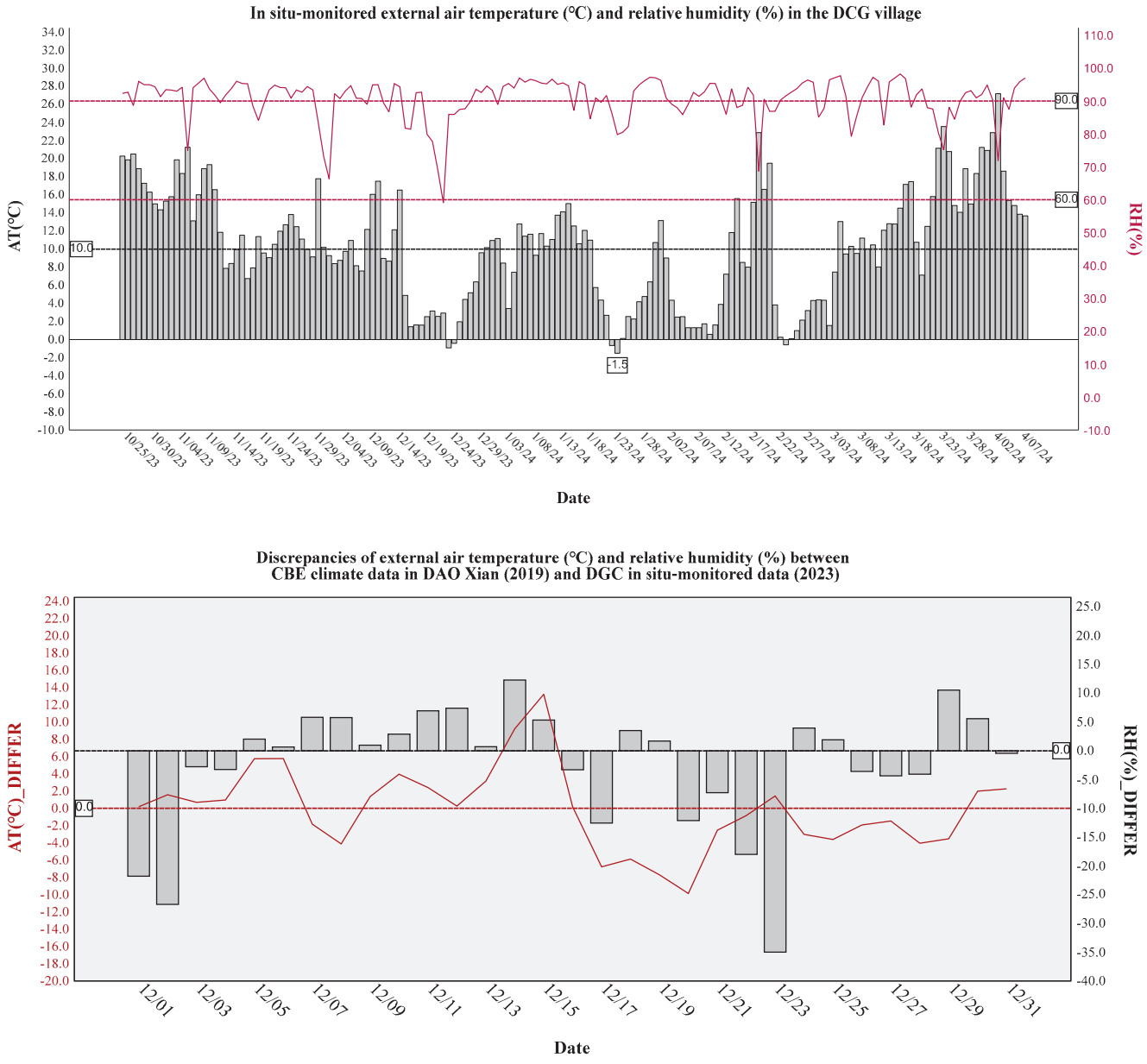
Traditional rammed earth structures are susceptible to erosion by rainwater; therefore, construction work must be carried out in dry weather with minimal interruptions due to rainfall. This requirement is usually met with two approaches: improving the inherent resistance of the walls to erosion by rainwater and constructing temporary shelters on site. As the village is classified as economically underprivileged and has limited technical resources, the cost-effectiveness of constructing rammed earth houses compared to conventional local brick and concrete buildings is paramount to increasing community interest. As the integration of temporary shelters would significantly raise construction costs by at least 50%, this solution poses an economic challenge. Therefore, in the context of the current socioeconomic situation in rural areas, prioritizing measures to improve the resistance of walls to rainwater erosion proves to be a more viable strategy for advancing construction successfully.

Figure 6 shows a comparable climate condition between the microclimate of the village and the climate data of the neighboring county concerning the CBE climate tool. Considering the frequency of climate changes in recent years, natural disasters and challenges are frequent in Chinese rural areas. Therefore, referencing the monitored microclimate data is more significant in analyzing the hydrothermal performance of renovated rammed earth houses in this case study.




(**a**)

**Figure 6.** *Cont.*




(**b**)

**Figure 6.** Microclimate data included external air temperature (°C) and relative humidity (%) from CBE climate tool and on−site. (**a**) is the climate data analysis derived from the CBE climate tool [84]. (**b**) Top is the outdoor temperature and relative humidity derived from in−situ monitoring by HOBO sensors in winter. Bottom is the discrepancies of external dry bulb air temperature and relative humidity between adjacent county's climate data from CBE climate tool, Daoxian, CHN, and the climate data monitored on−site in the village.

## 4. Results

This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions that can be drawn.

The internal structure of traditional rammed earth walls in the village, with many wood and bamboo strips embedded to ensure the strength and stability of the rammed earth walls, is analyzed. Based on the on-site observations, approximately 50% of the wall volume is estimated to be filled with bamboo strips, wood strips, and pebbles. Despite

clear traces of ramming and scaffold installation, the construction technique resembles a fill-based wattle and daub method. The density and compressive strength of the existing rammed earth wall are relatively low. A step-by-step repair of the wall is not feasible due to the interlaced network of embedded strips throughout its structure, as Figure 7 shows.

**Figure 7.** The internal structure of the earthen walls in the village's traditional rammed earth buildings shows remnants of the traditional formwork and scaffolding used in construction.

Concurrently, the recently constructed cement-stabilized rammed earth wall was structured as a load-bearing entity using a mixture of soil, sand, gravel, and cement. This homogenously blended composition resulted in increased compressive strength of the earth wall of over 2 MPa as tested in the Kunming University of Science and Technology lab and in situ and adequately met the structural load requirements. No additional horizontal or vertical banding structural components were incorporated within the wall to maintain the material's compacted density. Owing to its point-by-point repairability, the wall can be repaired or reconstructed incrementally depending on where the damage is located, whether in the original construction or future maintenance work.

By analyzing the renovation process of existing houses and the construction process of new houses, it has been found that traditional earth-built walls are prone to collapse under high humidity and light rainfall. Figure 8a–c show the actual occurrence of the study case, where the existing preserved rammed earth wall collapsed unpredictably during the construction process due to the constraints of the construction conditions under the influence of natural rainfall. The construction site personnel adjusted the design of the collapsed earth material in light of the actual situation, remixed it, and completed the masonry. Figure 8d shows that the new rammed earth wall, with the addition of cement, can continue to be built so that it does not collapse even in high humidity, light rain, and a wet environment.

Mustafa and Al-Amoudi [13] provided a comprehensive analysis of the various factors affecting the use of earth as a building material, including adding stabilizers. Cement-stabilized rammed earth construction can, to some extent, enhance the strength of the soil. However, Mustafa and Al-Amoudi [13] also pointed out that the hydration of the cement destroys the original properties of the soil and can result in bigger environmental problems. This case study is based on a rural area with low resource allocation and low technology, where upgrading the quality of housing is the primary goal to be accomplished at this time. Although there is room for further optimization in the use of cement-stabilized rammed earth construction, compared to the practice of residents of randomly demolishing brick and reinforced concrete, the low cost of cement-stabilized rammed earth construction and the indoor thermal performance of cement-stabilized rammed earth construction, compared to that of brick and reinforced concrete, make them relatively optimal choices for the villagers in this area.

(**a**) (**b**) (**c**)

(**d**)

**Figure 8.** Water resistance performance of rammed earth walls with and without the addition of cement in a harsh construction environment and in high humidity and light rain. (**a**) shows the preserved existing rammed earth wall at the beginning of construction; (**b**) shows the collapse of an area of retained traditional rammed earth wall due to sudden rainfall during construction; (**c**) shows the re-mixing of collapsed earth wall materials and re-laying of masonry in the form of adobe bricks in the collapsed position, connecting the new rammed earth wall with the retained rammed earth wall; (**d**) shows the relatively high resistance performance of the new rammed earth wall in the face of a wet and watery construction environment.

This empirical observation presents qualitative evidence supporting the better water resistance of cement-stabilized rammed earth walls than unmodified raw rammed earth walls. From a construction organization perspective, this performance suggests a beneficial influence on rural construction behavior at the minimum management level through adopting more resilient practices, such as integrating cement into rammed earth.

In addition, in conjunction with the perspective of local people's living demand, a survey revealed that local villagers still adhere to a relatively traditional way of life, characterized by practices such as using rammed earth as indoor flooring, maintaining fire pits for cooking and preserving food, storing firewood both indoors and outdoors, and constructing dry toilets and bathhouses made of tree bark outside the main rammed earth structures, as shown in Figure 9. All activities associated with water supply, such as laundry, food preparation, and dishwashing, are carried out in outdoor areas adjacent to the main rammed earth buildings. These practices are necessary because the villagers are exposed to harsh environmental conditions that span extreme winters and summers, which are very uncomfortable for them. Most importantly, the villagers have foregone the conventional practice of indoor toilets because of concerns regarding the poor waterproofing performance of rammed earth structures. They have had to adjust their living habits and movement patterns to safeguard the integrity of the building walls. Therefore, adding cement to the earth wall and combining modern mechanized ramming methods greatly improve the strength and compacting density of the wall. The durability and tolerance of the interior space and wall structure are higher, to a certain extent, for the compatibility of traditional living habits as well as modern living habits between the old, middle-aged, and young generations of local residents.

**Figure 9.** Living habitats in the village studied.

The greater strength and water resistance achieved by incorporating cement into rammed earth walls represent a remarkable advance over conventional raw earth construction. However, despite these improvements, such walls are still poorly suited for shower rooms exposed to high humidity and water from washing activities over long periods. Therefore, it is imperative to undertake additional waterproofing measures for bathrooms.

Construction cost is another critical factor in evaluating the sustainability of adding cement to earth walls for housing improvements in rural areas. A comparative analysis was conducted on the rammed earth buildings of the collective properties and the brick houses constructed simultaneously in the same village. This study revealed differences between the new rammed earth buildings and the brick houses built by the villagers, apart from the influence of climatic factors on the construction efficiency of both types of buildings, as detailed in Table 3.

**Table 3.** The differences in time, cost, and labor input between cement-stabilized rammed earth (CSRE) construction and fired brick building in the same village.

| Items | Cement-Stabilized Rammed Earth Building | Fired Brick Building |
|---|---|---|
| The launch date of construction | 1 October 2021 | 1 March 2021 |
| Date of handover | 6 July 2022 | 31 December 2022 |
| Story | 2 | 3 |
| Material cost/$m^2$ (CNY) | 500 | 1000 |
| Wall thickness (mm) | 350 | 180 |
| Daily average labor input | 5 | 3 |

## 5. Discussion

This study analyzed the effects of using cement-stabilized rammed earth construction in rural areas of southeast China by using software simulations and case studies in parallel.

In rural areas of China, limited economic resources and underdeveloped infrastructure have hindered the adoption of modern technologies and construction materials to improve the overall standard of buildings. Despite these challenges, the long-standing cultural practice of using rammed earth dwellings and local beliefs have driven and welcomed technological advances in renovating rammed earth construction.

This study investigated the effects of implementing cement-stabilized rammed earth construction in rural southeastern China through a combination of software simulations

and case studies. Challenges such as limited economic resources and lack of infrastructure have hindered the adoption of modern building technology in this region. Using rammed earth construction was critical to the project's progress, considering economic, social, cultural, and environmental factors.

With the clash between traditional practices and modern lifestyle preferences becoming more apparent across generations, the adoption of cement-stabilized rammed earth construction has emerged as a practical solution that addresses cost-effectiveness, convenience, comfort, and the preservation of local building customs. Analysis of simulation data and on-site construction evidence showed that using cement-stabilized rammed earth walls led to higher carbon emissions than traditional earthen construction, almost half that of a reinforced concrete frame system commonly used in the region. Moreover, despite the higher emissions, incorporating cement into the rammed earth walls resulted in a 50% cost reduction compared to building a house with 180 mm thick brickwork. In addition, this method improved the structure's resistance to sudden weather changes during the construction phase, surpassing the durability of traditional earth, brick, and reinforced concrete buildings.

This study relies more on integrating software simulations and site-specific studies to evaluate the cement-stabilized rammed earth construction holistically. This study shows that rammed earth construction with cement added is superior to traditional raw earth construction in terms of construction quality and technical durability and superior to reinforced concrete frame and brick masonry structures in terms of economic efficiency and environmental friendliness. However, looking at it from a broader perspective, adding cement is only suitable for regions with limited resources and technology, with an urgent need for safe housing and improving the overall environment. However, it is not the best solution for promoting the low-carbon development of buildings worldwide. As the economic level of rural areas rises, further investigation will inevitably be conducted into how to incorporate rural rammed earth construction into the raw earth construction and semi-fabricated assembly construction system. At the same time, how to collect and improve the database for software simulation through the continuous practice of rural rammed earth construction is worthy of more in-depth study.

## 6. Conclusions

Cement stabilizers are somehow workable for low-resource areas in particular economic and socio-cultural conditions. The environmental impact of adding cement to raw earth is inevitable. However, construction organizations' economic benefits and convenience formed a preliminary preference for those living locally to verify the urgency of living demand and ecological friendliness, which can be related to the conflicts between human-centered and nature-centered perspectives in a specific development context. This case study analyzed the necessity of cement stabilization in the context of low rural resources and rough living habits. The results proved to be adverse in terms of environmental performance but beneficial in their economic and socio-cultural aspects. Instead, exploring an eco-binder for future practice is necessary to decrease the dependence on cement further. At the same time, this can be achieved by simultaneously guiding and updating the living habits of local human beings and forming an intergenerational integration of habits to strengthen local people's awareness of the construction of low-carbon green buildings and to reduce waste and the demand for resources in their living habits, thus reducing the redundancy of the functional design of the building as well as the pursuit of decorative components that "have a face".

**Author Contributions:** Conceptualization, S.D., W.B. and J.X.; methodology, S.D.; software, S.D.; validation, W.B. and J.X.; formal analysis, S.D.; investigation, S.D.; resources, S.D.; data curation, W.B. and J.X.; writing—original draft preparation, S.D.; writing—review and editing, S.D. and J.X.; visualization, S.D.; supervision, W.B.; project administration, J.X.; funding acquisition, S.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Chan Cheung Mun Chung Charitable Fund, grant number IR91/9906.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author due to privacy.

**Acknowledgments:** The authors wish to thank Yong Dai, Xingda Guo, and Tony Ng from Chan Cheung Mun Chung Charitable Fund Ltd. for generously sharing their materials about the renovation of rural rammed earth household project, and special thanks go to the villagers for their kind help.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Wang, X. *Research on Symbiotic Development of Urbanand Rural Areas*; College of Public Administration Nanjing Agricultural University: Nanjing, China, 2015.
2. Ministry of Housing and Urban-Rural Development of China. *Statistical Yearbook of Urban-Rural Construction 2022*; China Statistics Press: Beijing, China, 2023.
3. Tang, G. *Appropriate Technology System and Construction Mode for Rural Architecture*; Huazhong University of Science and Technology Press Co.: Wuhan, China, 2021.
4. Wang, H.L. An analysis of the reasons for the formation of rural 'hollow villages' and countermeasures to solve the problem. *Rural. Econ.* **2005**, *9*, 21–22.
5. Li, Y.-R.; Cao, L.-Z.; Wang, P.-Y.; Chang, G.-J. Rural living environment improvement and rural revitalization. *J. Nat. Resour.* **2022**, *37*, 96–109. [CrossRef]
6. Liu, Y.; Zang, Y.; Yang, Y. China's rural revitalization and development: Theory, technology and management. *J. Geogr. Sci.* **2020**, *30*, 1923–1942. [CrossRef]
7. GFDRR; The World Bank. *China's Experience in Disaster Risk Management*; GFDRR: Washington, DC, USA; The World Bank: Washington, DC, USA, 2020.
8. Academy of Disaster Reduction and Emergency Management, Ministry of Emergency Management; Ministry of Education; School of National Safety and Emergency Management, Beijing Normal University; National Disaster Reduction Center of China, Ministry of Emergency Management; International Federation of Red Cross and Red Crescent Societies. *Global Natural Disaster Assessment Report*; American Society of Civil Engineers: Reston, VA, USA, 2022.
9. Burroughs, S. Soil Property Criteria for Rammed Earth Stabilization. *J. Mater. Civ. Eng.* **2008**, *20*, 264–273. [CrossRef]
10. Marc Auzet, J.G. *Da Bai Yi Phase 2_Synthese on Soil Analysis*; Laboratory report; Kunming, China, 2018.
11. Wang, Y.; Wang, M.; Liu, K.; Pan, W.; Yang, X. Shaking table tests on seismic retrofitting of rammed-earth structures. *Bull. Earthq. Eng.* **2016**, *15*, 1037–1055. [CrossRef]
12. Ciancio, D.; Beckett, C. *Rammed Earth Construction: Cutting-Edge Research on Traditional and Modern Rammed Earth*; CRC Press: Boca Raton, FL, USA, 2015.
13. Mustafa, Y.M.H.; Al-Amoudi, O.S.B.; Zami, M.S.; Al-Osta, M.A. Assessment of the Suitability of Earth as a Construction Material from Experimental and Numerical Perspectives: A Critical Review. *Int. J. Géoméch.* **2023**, *23*, 03123003. [CrossRef]
14. Pelé-Peltier, A.; Charef, R.; Morel, J.-C. Factors affecting the use of earth material in mainstream construction: A critical review. *Build. Res. Inf.* **2023**, *51*, 119–137. [CrossRef]
15. Jun, M.; Zhou, T.; Jiang, W.; Lu, L.; Wang, S.; Li, Q. A Study on the Localization of Modern Rammed Earth Technology in Rural Construction and Demonstration Projects. *J. Archit.* **2016**, *6*, 573.
16. Xu, Y.; Yao, Y. Informal Institutions, Collective Action, and Public Investment in Rural China. *Am. Politi. Sci. Rev.* **2015**, *109*, 371–391. [CrossRef]
17. UNEP. Building Materials and the Climate: Constructing a New Future. In *Building Materials and the Climate: Constructing a New Future*; Dyson, A., Keena, N., Lokko, M.-L., Ciardullo, C., Eds.; United Nations Environment Programme: Nairobi, Kenya, 2023.
18. Touati, K.; Benzaama, M.-H.; El Mendili, Y.; Le Guern, M.; Streiff, F.; Goodhew, S. Hygrothermal and Economic Analysis of an Earth-Based Building Using In Situ Investigations and Artificial Neural Network Modeling for Normandy's Climate Conditions. *Sustainability* **2023**, *15*, 13985. [CrossRef]
19. Ciancio, D.; Jaquin, P.; Walker, P. Advances on the assessment of soil suitability for rammed earth. *Constr. Build. Mater.* **2013**, *42*, 40–47. [CrossRef]
20. Morel, J.C.; Bui, Q.B.; Hamard, E. Weathering and durability of earthen material and structures. In *Modern Earth Buildings*; Woodhead Publishing: Delhi, India, 2012; pp. 282–303.
21. Parracha, J.L.; Lima, J.; Freire, M.T.; Ferreira, M.; Faria, P. Vernacular Earthen Buildings from Leiria, Portugal—Material Characterization. *Int. J. Arch. Heritage* **2021**, *15*, 1285–1300. [CrossRef]

22. Ma, C.; Chen, B.; Chen, L. Variables controlling strength development of self-compacting earth-based construction. *Constr. Build. Mater.* **2016**, *123*, 336–345. [CrossRef]
23. Haider, A.B.; Iravanian, A.; Selman, M.H.; Ekinci, A. Using Waste PET Shreds for Soil Stabilization: Efficiency and Durability Assessment. *Int. J. Geosynth. Ground Eng.* **2023**, *9*, 48. [CrossRef]
24. Martín-Del-Rio, J.J.; Canivell, J.; Falcón, R.M. The use of non-destructive testing to evaluate the compressive strength of a lime-stabilised rammed-earth wall: Rebound index and ultrasonic pulse velocity. *Constr. Build. Mater.* **2020**, *242*, 118060. [CrossRef]
25. Malkanthi, S.; Wickramasinghe, W.; Perera, A. Use of construction waste to modify soil grading for compressed stabilized earth blocks (CSEB) production. *Case Stud. Constr. Mater.* **2021**, *15*, e00717. [CrossRef]
26. Fodde, E. Traditional Earthen Building Techniques in Central Asia. *Int. J. Archit. Herit.* **2009**, *3*, 145–168. [CrossRef]
27. Fabbri, A.; Morel, J.C.; Aubert, J.E.; Bui, Q.B.; Gallipoli, D.; Reddy, B. *Testing and Characterisation of Earth-Based Building Materials and Elements*; State-of-the-Art Report of the RILEM TC 274-TCE; Springer International Publishing: Berlin/Heidelberg, Germany, 2022.
28. Niroumand, H.; Barcelo, J.A.; Saaly, M. The Role of Archeology on Earth Buildings and Earth Architecture in the World. *Indian J. Sci. Technol.* **2016**, *9*, 25. [CrossRef]
29. Bruno, A.W.; Gallipoli, D.; Perlot, C.; Mendes, J. Mechanical behaviour of hypercompacted earth for building construction. *Mater. Struct.* **2017**, *50*, 160. [CrossRef]
30. Kandamby, G.W.T.C. Long Term Existence of Cement Stabilized Rammed Earth Walls. *Eng. J. Inst. Eng. Sri Lanka* **2019**, *52*, 37–43. [CrossRef]
31. Heringer, A.; Howe, L.B.; Rauch, M. *Upscaling Earth: Mateiral, Process, Catalyst*; Gta Verlag: Zurich, Switzerland, 2022.
32. Kosarimovahhed, M.; Toufigh, V. Sustainable usage of waste materials as stabilizer in rammed earth structures. *J. Clean. Prod.* **2020**, *277*, 123279. [CrossRef]
33. Lydia Kiroff, H.R. Sustainable Construction Technologies: Earth Buildings in New Zealand. In Proceedings of the Second International Conference on Sustainable Construction Mateirals and Technologies, Ancona, Italy, 28–30 June 2010.
34. Egenti, C.; Khatib, J.M. Sustainability of compressed earth as a construction material. In *Sustainability of Construction Materials*; Woodhead Publishing: Delhi, India, 2016; pp. 309–341.
35. Kutschke, L. Social Life-Cycle Assessment for Building Materials. In *Examining the Environmental Impacts of Materials and Buildings*; Brownell, B.E., Ed.; IGI Global: Hershey, PA, USA, 2020; pp. 217–250.
36. Khadka, B. Rammed earth, as a sustainable and structurally safe green building: A housing solution in the era of global warming and climate change. *Asian J. Civ. Eng.* **2019**, *21*, 119–136. [CrossRef]
37. Zhang, Y.; Jiang, S.; Quan, D.; Fang, K.; Wang, B.; Ma, Z. Properties of Sustainable Earth Construction Materials: A State-of-the-Art Review. *Sustainability* **2024**, *16*, 670. [CrossRef]
38. Bui, Q.-B.; Bui, T.-T.; El-Nabouch, R.; Thai, D.-K. Vertical Rods as a Seismic Reinforcement Technique for Rammed Earth Walls: An Assessment. *Adv. Civ. Eng.* **2019**, *2019*, 1285937. [CrossRef]
39. Venkatarama Reddy, B.V. Stabilised soil blocks for structural masonry in earth construction. In *Modern Earth Buildings*; Woodhead Publishing: Delhi, India, 2012; pp. 324–363.
40. Silva, R.A.; Oliveira, D.V.; Schueremans, L.; Miranda, T.; Machado, J. Shear behaviour of rammed earth walls repaired by means of grouting. In Proceedings of the 9th International Masonry Conference 2014, Guimarães, Portugal, 7–9 July 2014.
41. El-Nabouch, R.; Bui, Q.-B.; Perrotin, P.; Plé, O. Shear Parameters of Rammed Earth Material: Results from Different Approaches. *Adv. Mater. Sci. Eng.* **2018**, *2018*, 8214604. [CrossRef]
42. Pavan, G.; Ullas, S.; Rao, K.N. Shear behavior of cement stabilized rammed earth assemblages. *J. Build. Eng.* **2020**, *27*, 100966. [CrossRef]
43. Jayasinghe, M.T.R.; Jayasinghe, C.; Kariyawasam, K.K.G.K.D.; De Silva, L.I.N. Semi-Tiered Housing for Laterite Earth Sloping Lands-A Sustainable Solution with Alternative Materials and Methods. *J. Green Build.* **2018**, *13*, 56–72. [CrossRef]
44. Matos, A.M.; Varum, H. Self-Compacting Earth-Based Composites: Mixture Design and Multi-Performance Characterisation. *Buildings* **2022**, *12*, 612. [CrossRef]
45. Laghi, V.; Palermo, M.; Trombetti, T.; Schildkamp, M. Seismic-Proof Buildings in Developing Countries. *Front. Built Environ.* **2017**, *3*, 49. [CrossRef]
46. Correia, M.; Lourenco, P.B.; Varum, H. *Seismic Retrofitting_Learning from Vernacular Architecture*; CRC Press: Boca Raton, FL, USA, 2015.
47. Preciado, A.; Santos, J.C. Rammed earth sustainability and durability in seismic areas as a building material. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *410*, 012108. [CrossRef]
48. Mileto, C.; Vegas, F.; Soriano, L.G.; Cristini, V. *Vernacular Architecture:Towards a Sustainable Future*; CRC Press: Boca Raton, FL, USA, 2014.
49. Niroumand, H.; Zain, M.; Jamil, M. Various Applications of Earth Architecture. *Procedia Soc. Behav. Sci.* **2013**, *89*, 231–236. [CrossRef]
50. Adam, E.; Jones, P. Thermophysical properties of stabilised soil building blocks. *Build. Environ.* **1995**, *30*, 245–253. [CrossRef]
51. Petcu, C.; Dobrescu, C.F.; Dragomir, C.S.; Ciobanu, A.A.; Lăzărescu, A.V.; Hegyi, A. Thermophysical Characteristics of Clay for Efficient Rammed Earth Wall Construction. *Materials* **2023**, *16*, 6015. [CrossRef] [PubMed]

52. Chintha Jayasinghe, D.J. Buddhika Dissanayake, thermal performance of composite walls made out of recycled building wastes and stabilized rammed earth. In Proceedings of the NBRO Research Symposium 2015—Resilient Built Environment, Colombo, Sri Lanka, 22 December 2015.
53. Leitão, D.; Barbosa, J.; Soares, E.; Miranda, T.; Cristelo, N.; Briga-Sá, A. Thermal performance assessment of masonry made of ICEB's stabilised with alkali-activated fly ash. *Energy Build.* **2017**, *139*, 44–52. [CrossRef]
54. Tinsley, J.; Pavía, S. Thermal performance and fitness of glacial till for rammed earth construction. *J. Build. Eng.* **2019**, *24*, 100727. [CrossRef]
55. Carrobé, A.; Rincón, L.; Martorell, I. Thermal Monitoring and Simulation of Earthen Buildings: A Review. *Energies* **2021**, *14*, 2080. [CrossRef]
56. Navarro, L.; de Gracia, A.; Niall, D.; Castell, A.; Browne, M.; McCormack, S.J.; Griffiths, P.; Cabeza, L.F. Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system. *Renew. Energy* **2016**, *85*, 1334–1356. [CrossRef]
57. Lovec, V.B.; Jovanovic-Popovic, M.; Zivkovic, B.D. The thermal behavior of rammed earth wall in traditional house in Vojvodina: Thermal mass as a key element for thermal comfort. *Therm. Sci.* **2018**, *22* (Suppl. S4), S1143–S1155. [CrossRef]
58. Samadianfard, S.; Toufigh, V. Stabilization effect on the hygrothermal performance of rammed earth materials. *Constr. Build. Mater.* **2023**, *409*, 134025. [CrossRef]
59. Marais, P.; Littlewood, J.; Karani, G. The use of polymer stabilised earth foundations for rammed earth construction. In Proceedings of the 7th International Conference on Sustainability and Energy in Buildings (SEB), Lisbon, Portugal, 1–3 July 2015; Elsevier Science Bv: Amsterdam, The Netherlands, 2015.
60. Ciurileanu, G.T.; Horvath, I.B. The Use of Cement Stabilized Rammed Earth for Building a Vernacular Modern House. *Bul. Institutului Politeh. Din Lasi. Sect. Constr. Arhit.* **2012**, *25*, 37.
61. Niroumand, H.; Akbari, R.; Khanlari, K.; Gültekin, A.B.; Barcelo, J.A. A systematic literature review of rammed earth walls. *Soil Mech. Found. Eng.* **2021**, *58*, 295–301. [CrossRef]
62. Marsh, A.T.M.; Kulshreshtha, Y. The state of earthen housing worldwide: How development affects attitudes and adoption. *Build. Res. Inf.* **2021**, *50*, 485–501. [CrossRef]
63. Ciancio, D.; Boulter, M. Stabilised rammed earth: A case study in Western Australia. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2012**, *165*, 141–154. [CrossRef]
64. Abd El Rahman, M.A. A Review of the Construction Techniques for Earthen Buildings, with a Brief Analysis of the Case of the Kingdom of Saudi Arabia. Ph.D. Dissertation, Heriot-Watt University, Edinburgh, Scotland, 2012.
65. Zhou, T.; Peng, D.; Mu, J.; Hugo, C.G.; Quentin, A.R. Research and Application of Modern Rammed Earth Wall Construction Technology. *Constr. Technol.* **2012**, *41*, 370.
66. Giuffrida, G.; Caponetto, R.; Cuomo, M. An overview on contemporary rammed earth buildings: Technological advances in production, construction and material characterization. In Proceedings of the SBE19 Milan—Resilient Built Environment for Sustainable Mediterranean Countries, Milan, Italy, 4–5 September 2019.
67. King, B. *Review of Earthen Building Codes and Standards from Around the World*; Ecological Building Network: San Rafael, CA, USA, 2019.
68. Thompson, D.; Augarde, C.; Osorio, J.P. A review of current construction guidelines to inform the design of rammed earth houses in seismically active zones. *J. Build. Eng.* **2022**, *54*, 104666. [CrossRef]
69. Maniatidis, V.; Walker, P. *A Review of Rammed Earth Construction for DTi Partners in Innovation Project Developing Rammed Earth for UK Housing*; University of Bath: Bath, UK, 2003.
70. *NZS 4297:1998*; NZD4297-1998-Engineering Design of Earth Buildings [Building Code Compliance Documents B1 (VM1), B2 (AS1)]. Standards New Zealand: Wellington, New Zealand, 1998.
71. Andrew Alcorn, P.W. *New Zealand Building Materials Embodied Energy Coefficients Database Volume II—Coefficients*; Centre for Building Performance Research Victoria University of Wellington: Wellington, New Zealand, 1998.
72. Schroeder, H. Modern earth building codes, standards and normative development. In *Modern Earth Buildings*; Woodhead Publishing: Delhi, India, 2012; pp. 72–109.
73. Fulton, L.; Beauvais, B.; Brooks, M.; Kruse, S.; Lee, K. Sustainable Residential Building Considerations for Rural Areas: A Case Study. *Land* **2020**, *9*, 152. [CrossRef]
74. Adegun, O.B.; Adedeji, Y.M.D. Review of economic and environmental benefits of earthen materials for housing in Africa. *Front. Arch. Res.* **2017**, *6*, 519–528. [CrossRef]
75. van Oorschot, J.; Sprecher, B.; Rijken, B.; Witteveen, P.; Blok, M.; Schouten, N.; van der Voet, E. Toward a low-carbon and circular building sector: Building strategies and urbanization pathways for the Netherlands. *J. Ind. Ecol.* **2023**, *27*, 535–547. [CrossRef]
76. Ben-Alon, L.; Loftness, V.; Harries, K.A.; Hameen, E.C. Integrating Earthen Building Materials and Methods into Mainstream Construction Using Environmental Performance Assessment and Building Policy. *IOP Conf. Series Earth Environ. Sci.* **2019**, *323*, 012139. [CrossRef]
77. Jun, M. Exploring, Renewing and Inheriting the Tradition of Earthen Construction. *Archit. J.* **2016**, *4*, 1–7.
78. Rael, R. *Earth Architecture*; Lee, L., Ball, D., Eds.; Princeton Architectural Press: New York, NY, USA, 2009.
79. Jaquin, P. History of earth building techniques. In *Modern Earth Buildings*; Woodhead Publishing: Delhi, India, 2012; pp. 307–323.

80. UNESCO WHC. World Heritage Earthen Architecture Programme (WHEAP). 2017. Available online: https://whc.unesco.org/en/earthen-architecture/ (accessed on 2 May 2024).
81. Petrovic, B.; Myhren, J.A.; Zhang, X.; Wallhagen, M.; Eriksson, O. Life Cycle Assessment of Building Materials for a Single-family House in Sweden. *Energy Procedia* **2019**, *158*, 3547–3552. [CrossRef]
82. Han, T.; Huang, Q.; Zhang, A.; Zhang, Q. Simulation-Based Decision Support Tools in the Early Design Stages of a Green Building—A Review. *Sustainability* **2018**, *10*, 3696. [CrossRef]
83. Tartarini, F.; Schiavon, S.; Cheung, T.; Hoyt, T. CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations. *SoftwareX* **2020**, *12*, 100563. [CrossRef]
84. Betti, G.; Tartarini, F.; Nguyen, C.; Schiavon, S. CBE Clima Tool: A free and open-source web application for climate analysis tailored to sustainable building design. *Build. Simul.* **2024**, *17*, 493–508. [CrossRef]
85. Sun, F. Chinese Climate and Vernacular Dwellings. *Buildings* **2013**, *3*, 143–172. [CrossRef]
86. Chao, Q.C. *China Climate Bulletin (2022)*; Meteorological Press: Beijing, China, 2023.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# Coupling and Coordination Development, Spatiotemporal Evolution, and Driving Factors of China's Digital Countryside and Inclusive Green Growth in Rural Areas

**Liupeng Chen [1], Yiting Wang [1], Yingzheng Yan [2], Ziwei Zhou [2], Bangsheng Xie [1,2,*] and Xiaodong You [2,*]**

[1] School of Rural Revitalisation, Fujian Agriculture and Forestry University, Fuzhou 350002, China; clp2000@fafu.edu.cn (L.C.); wyt@fafu.edu.cn (Y.W.)
[2] School of Economics and Management, Fujian Agriculture and Forestry University, Fuzhou 350002, China; fjyyz@fafu.edu.cn (Y.Y.); zzw1224@fafu.edu.cn (Z.Z.)
* Correspondence: 000q091020@fafu.edu.cn (B.X.); 000q091019@fafu.edu.cn (X.Y.); Tel.: +86-139-0500-6665 (B.X.); +86-138-0506-4421 (X.Y.)

**Abstract:** Inclusive green growth is an effective strategy for achieving sustainable development in rural areas. In the digital economy era, it is crucial to examine whether rural digital development and inclusive green growth can be harmoniously integrated. This study investigates the spatial and temporal evolution of the coupled coordination between digital village construction and rural inclusive green growth in China. Utilizing panel data from 30 provinces from 2011 to 2022, we assess development levels using the entropy weighting method and analyze interdependencies with a coupling coordination model. The results indicate an upward trend in coupling coordination, with significant regional disparities, and it is slowly taking on the characteristics of spatial clustering. Economically advanced regions exhibit higher coordination levels, attributed to stronger economic foundations and better fiscal resources, enabling effective investments in digital infrastructure and green growth initiatives. Additionally, factors such as urbanization rate, innovation levels, reduction in natural disasters, increased financial support for agriculture, and improved large-scale operations positively contribute to this coordination. These findings offer insights for targeted regional development strategies, enhancing the synergy between digital transformation and sustainable rural development.

**Keywords:** digital rural development; rural inclusive green growth; coupled coordination; spatial and temporal evolution

**Citation:** Chen, L.; Wang, Y.; Yan, Y.; Zhou, Z.; Xie, B.; You, X. Coupling and Coordination Development, Spatiotemporal Evolution, and Driving Factors of China's Digital Countryside and Inclusive Green Growth in Rural Areas. *Sustainability* **2024**, *16*, 5583. https://doi.org/10.3390/su16135583

Academic Editors: Marc A. Rosen, Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Baojie He and Shi Cheng

Received: 17 May 2024
Revised: 20 June 2024
Accepted: 26 June 2024
Published: 29 June 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Since its inception at the Rio+20 Summit in 2012, the notion of "inclusive green growth" has gained prominence globally as an exemplar of sustainable development that harmoniously integrates environmental tolerance and social equity [1] (pp. 144–155). Many nations have begun to adopt new development models centered on "inclusive green growth" since the United Nations unveiled new sustainable development objectives in 2016. One approach to inclusive green growth entails sustainable and efficient natural resource utilization while ensuring that the pollution levels remain within the planet's tolerance capacity. This approach also entails a paradigm shift in how society perceives the interplay between economic, social, and environmental development [2,3] (pp. 3–20, pp. 115–121). Green growth, which relies on advancements in green technology and the development of renewable energy sources, ensures a fundamental living environment, offering safer conditions and healthier food options. This approach not only contributes to environmental sustainability but also fosters the realization of the potential and creativity of professionals in this sector, enhancing their personal development and career fulfillment. In order to meet the public's demand for an improved environment, it is imperative that the inclusive development of society be supported by green growth, which entails a paradigm

shift in economic development facilitated by a rational upgrading of the industrial structure and the promotion of environmental decarbonization and greening. Green growth should be predicated on socially inclusive growth; as Maslow's Hierarchy of Needs posits, individuals only attain the necessities that are fundamental for their survival. Since the advent of the Industrial Revolution, the rapid economic development of nations and regions, particularly in rural areas, has inevitably given rise to numerous disadvantages [4,5] (pp. 1–25, pp. 196–202). For instance, the "cake" of rural economic development has not been equitably distributed, resulting in significant disparities between urban and rural regions, and the degradation of ecosystems, the environment, and agricultural resources is progressively becoming more prominent [6] (pp. 41–65). Despite facing numerous challenges in rural development, the Chinese government has demonstrated a strong commitment to its improvement. Initiatives began in earnest in 2003 with the adoption of the "scientific outlook on development" as a guiding ideology. By 2005, this commitment had expanded to include the goal of "building a resource-saving and environmentally friendly society". The importance of these initiatives grew following the 18th National Congress of the Communist Party of China, which introduced the "five-in-one" strategy. This strategy emphasizes ecological civilization and integrates it into all aspects of socioeconomic development, promoting a shift towards greener production methods. As the world's most populous developing country and its second largest economy, China's approach to inclusive green development in rural areas is poised to enhance the quality of rural life domestically and also offers a sustainable development model that could influence global economic progress, particularly among other developing nations.

The digital economy, in the wake of the agricultural and industrial economies, has emerged as a significant catalyst for present and forthcoming global economic progress [7,8] (pp. 34–57, pp. 303–311). In recent years, China has been actively advancing its Digital China strategy. This strategy employs contemporary information technologies, such as the Internet, big data, and artificial intelligence, to upgrade the nation's governance systems and capabilities. Its goal is to significantly boost the digitalization of society and the economy, facilitating a significant advancement in information technology development. The construction of digital villages represents a specific application of the Digital China initiative in rural areas. As digital technologies have been unprecedentedly integrated into the rural economic and social fields in recent years, building digital villages is essential for advancing rural development, enhancing agricultural productivity and efficiency, and markedly boosting the living standards of rural communities. By integrating modern information technologies, rural areas can broaden e-commerce opportunities, increase access to educational and healthcare services, spur economic growth, and strengthen their ability to manage themselves sustainably and effectively. For instance, India's Digital India program aims to transform rural areas through digitalization, improving economic opportunities and social inclusion. Similarly, the European Union's Smart Villages strategy focuses on leveraging digital technologies to promote sustainable development in rural regions. These comparisons highlight the broader applicability of digital rural development strategies. These strategies address various challenges in rural communities, from social and economic issues to environmental concerns. In comparing China's digital village strategy with India's Digital India program and the EU's Smart Villages strategy, we observe several commonalities and differences. All three initiatives emphasize the enhancement of digital infrastructure, improvement of rural residents' quality of life, and promotion of sustainable development through digital technologies. However, there are notable differences in their approaches. India's program focuses more on e-governance and transparency, while China's strategy emphasizes the coordinated development of economy and environment. The EU's strategy places a stronger emphasis on social inclusion and community engagement alongside economic diversification. These comparisons highlight the universal applicability of digital rural development strategies and the potential for cross-regional learning and adaptation of best practices. Because digital village construction and the rural economy structure have progressed and changed at a rapid rate, it is crucial to determine

whether inclusive green growth development and digital village construction can coexist. The relationship between the development of digital villages and that of inclusive green growth in rural areas is predominately shaped by the following three factors:

(1) The economic impact of digital village development: Digital village projects can effectively reduce the economic disparities between urban and rural areas by enhancing the agricultural efficiency, expanding agricultural product markets, promoting rural entrepreneurship and employment, improving educational resources, and strengthening infrastructure and services. Specifically, smart agricultural technologies reduce costs and increase the incomes of farmers, and online market platforms enable farmers to directly reach a broader consumer base, increasing their product profitability. Digital tools provide new job opportunities and platforms for entrepreneurship in rural areas, while online education and training courses enhance skill sets and employment competitiveness. Improved infrastructure further enhances quality of life and economic vitality. These measures not only directly improve the economic levels of rural areas but also help narrow the economic gap between rural and urban areas by promoting equal access to resources. Moreover, by leveraging technological spillover and industrial competition, digital village construction can facilitate the upgrading and transformation of industrial infrastructure [9] (pp. 10–24). In the analysis of industrial competition mechanisms, the construction of digital villages facilitates rural enterprises and producers in accessing broader markets through advanced digital technologies and Internet platforms. This access encourages them to enhance the quality of their products and services to meet the needs of a more diverse consumer base. Regarding the spillover effects of technology, the high-tech solutions introduced by digital village initiatives—such as big data, the Internet of Things (IoT), and artificial intelligence (AI)—are not only directly implemented in agricultural production but also enhance the technological capabilities of other local economic sectors. The introduction and application of these technologies can lead to technological spillover effects, where technical knowledge and innovations are disseminated from one economic sector to others, elevating the overall technological standard and production efficiency of the region. Additionally, spillover has the potential to significantly boost the overall productivity factor of both the local and neighboring regions, enhance the performance of agricultural socialized services, and optimize the business environment for micro and small enterprises. Consequently, these improvements can directly impact the output level of the digital village [10,11] (pp. 5–10, pp. 61–80). For instance, in Guan County, Shandong Province, an innovative approach was taken to establish the "Guan County Agricultural Custody Full-Industry Chain Elements Trading Service Platform". Since its official launch, the platform has achieved a transaction volume exceeding CNY 4 million, saving over 10% in costs for villagers and social service entities.

(2) The effect that digital village development has on inclusivity: Digital rural construction promotes the development of rural digital governance by strengthening the hierarchical structure of the government and financing sector. This is primarily accomplished through the restructuring and optimization of three elements: rural people, land, and money [12,13] (pp. 41–53, pp. 114–132). Digital rural construction accelerates the supply of digital infrastructure, ensures livelihood services, and helps farmers meet their individualized needs [14,15] (pp. 27–40, pp. 132–140).

(3) The impact of digital village construction on the environment: The construction of digital villages has created a technical conduit for the transformation of the "two mountains" and is capable of resolving the issues of "de-energizing", "de-polluting", and "value transformation". Moreover, it has demonstrated considerable momentum in the domains of public low-carbon consumption oversight, green environmental transformation, and social governance oversight [16,17] (pp. 54–65, pp. 165–175). Over time, it has emerged as a novel trajectory that is spearheading sustainable development, low-carbon production, and green environmental protection. Specific

measures include deploying digital technologies for environmental monitoring systems to track the water, air, and soil quality in rural areas in real time, enabling timely responses to environmental issues. Precision and eco-friendly agricultural techniques, such as drip irrigation and organic farming, are promoted to reduce the use of fertilizers and pesticides, thereby minimizing their negative impacts on the environment. Environmental education and awareness are enhanced through digital platforms to increase the participation of rural residents in environmental protection. Furthermore, identifying and addressing new challenges brought about by digitalization, such as the management of electronic waste, ensures that technological debris does not compromise the environmental goals of projects.

The current body of literature primarily examines the effects of digital village development on the individual dimensions of inclusive green growth, such as the environment, society, and economy dimensions. However, research that specifically investigates the interplay between digital village development and coupled and coordinated development, which would further support the bidirectional relationship theory, is scarce. Furthermore, while numerous studies have examined inclusive green development in China as a whole, rural inclusive green growth has not been the focus of any of them. In order to accomplish this, in the present study, we endeavored to address the following three inquiries: Does the development of digital communities in China align with the principles of inclusive green rural expansion? What are the salient features that define its temporal and spatial progression? What are the factors affecting the coupling and harmonization of digital village development with inclusive green growth in the countryside?

Evaluation of the integrated and synchronized progress of digital village development and inclusive rural green growth is critical in this regard for the attainment of sustainable development objectives globally, with a particular emphasis on rural regions. Examining 30 provinces in China from 2011 to 2021, in this study, we attempted to construct an indicator evaluation system based on the connotations of the two indices. We used the indicator evaluation system, with some adjustments, to measure the rural inclusive green growth and digital village construction coupling coordination degrees of 30 provinces in China from 2011 to 2021. In addition, we analyzed the spatial and temporal evolution characteristics of the degrees of the coupling coordination of the two indices and their modified coupling coordination degrees using statistical analysis software and ArcGIS 10.8, providing a theoretical and practical foundation for advancing the coupling and synergy mechanism between rural inclusive green growth and digital village construction. The primary contributions of this study are as follows: Prior research has predominantly examined inclusive green growth at the macrolevel; however, it has not specifically examined inclusive green growth in rural areas characterized by rural attributes. In this study, we developed China's rural inclusive green growth indicator system by taking into account international comparability and the current state of affairs in China. The indicator system is based on the three dimensions of rural social inclusion, rural economic growth, and rural green development, with the connotation of rural inclusive green growth. Additionally, we analyzed the theoretical two-way relationship between digital village construction and rural inclusive green growth, as well as the temporal aspect of this relationship.

The subsequent sections are structured as follows: Section 2 undertakes a theoretical analysis of the coordinated and coupled relationship between digital village construction and rural inclusive green development in China. Section 3 constructs a systematic indicator system for rural inclusive green growth and digital village construction in China. The system measures the degree of coupling coordination between the two initiatives, with specific adjustments made. The spatial and temporal evolution of the coupled coordination degrees between rural inclusive green growth in China and digital village construction, as well as its revised coupled coordination degrees, are analyzed in Section 4. A summary of the study's conclusions and policy implications is presented in Section 5.

## 2. Theoretical Analysis

In light of the emergence of the digital economy, the progress of rural communities is inextricably linked to digital technology. The primary indicators of the digital village development contribution to inclusive green growth in rural areas are as follows:

(1) The information access effect: Agricultural business entities are susceptible to risk due to the unpredictability and volatility of the information on the market [18] (pp. 141–153). By mitigating the information asymmetry that exists between producers and the market, the establishment of a digital countryside enables the primary agricultural production and management sector to gain a more precise understanding of the market dynamics, facilitate timely decision making, and analyze its own resource endowment in accordance with the market demand through the utilization of big data models, which, in turn, improves the mode of production and fosters the advancement of high-quality agriculture [19] (pp. 68–89). Furthermore, as an outcome of resource integration, digital empowerment that facilitates rural governance modernization positively contributes to the safeguarding of farmers' rights. The implementation of big data technology and government affairs processing ensures the transparent, precise, and digitally intelligent progression of both. Moreover, it regulates the "use of people, money, and power" within the village, thereby safeguarding the rights and interests of farmers [20] (pp. 72–81). For example, in the area of personnel management, digital development can enhance the efficiency of systems that record and track the performance and duties of village officials and staff. Public access to this information ensures transparency and fairness in hiring processes. In terms of financial management, utilizing e-governance platforms to disclose rural financial expenditures, project bidding, and contract execution improves the fund usage transparency, allowing villagers to directly oversee the financial activities of their village committees. Regarding land management, establishing an electronic land registration system that records the rights to use each parcel of land and any ownership changes ensures the legality and transparency of land transactions and usage. An electronic land registration system would not only help prevent illegal land occupation and misuse but would also protect the land rights of farmers, thereby avoiding social issues caused by land disputes. Furthermore, information access not only offers rural inhabitants convenient access to healthcare but also access to a wide array of learning opportunities, and it also contributes to the achievement of urban–rural co-governance [14] (pp. 27–40) and the closing of the educational divide between the urban and rural sectors [21] (pp. 62–76). Telemedicine platforms provide professional medical counseling, diagnosis, and treatment services to rural residents, thereby addressing the issue of the limited medical resources in these regions. By facilitating access to online educational platforms, rural inhabitants can attain learning resources equivalent to those of their urban counterparts, thereby narrowing the educational divide that exists between the two regions.

(2) The technology diffusion effect: Digital technology enables the agricultural sector to achieve green and low-carbon transformation with regard to production. By leveraging agricultural big data platforms, the agricultural Internet of Things (IoT), GIS, and other technological advancements, one can efficiently acquire data pertaining to the physical conditions of light, humidity, temperature, air, soil water content, and nutrients, in addition to the nutritional statuses and health levels of crops. These data can then be transmitted to an intelligent growth control system where they are processed, and automated AI generates production and management strategies to mitigate these factors [22,23] (pp. 37–48, pp. 118–129). The digital empowerment of rural life ultimately benefits the pastoral ecosystem. The real-time monitoring and control of intelligent waste classification management and rural sewage treatment as well as an increase in their precision and efficacy in order to reduce environmental pollution are possible with the digital supervision and intelligent analysis systems of the entire process [24,25] (pp. 70–90, pp. 263–275). Furthermore, equipment and

personnel limitations frequently prevent the real-time monitoring of environmental changes and emissions from pollution sources in conventional rural environmental monitoring. Furthermore, by implementing remote sensing technology and sensors, it is possible to achieve the real-time monitoring of the rural environment to obtain early warnings, which would enhance the capacity for detecting natural disasters and issuing timely warnings, enabling appropriate actions to be taken to safeguard the rural ecological environment at its origin. Moreover, it would contribute to the development of a picturesque and harmonious countryside [26] (pp. 58–67).

Inclusive green growth implementation in rural regions has the following effects on digital village development:

(1) The "support" effect: Rural areas that are digitally empowered persistently encounter unidentified risks and challenges due to their innovative and disruptive nature. Increasing the human capital of farmers, promoting income growth, accelerating the urban–rural integration and development process, mitigating the digital "negative energy" effect at its source, and providing internal and external support for the "steady progress" construction of digital villages are all inclusive green growth objectives in rural areas [27] (pp. 68–77).

(2) The subsequent "lead effect": This approach to inclusive green rural development will direct the construction of digital villages. Rural regions that experience external disturbances or policy disruptions will expose any shortcomings and deficiencies in the establishment of rural harmony and the advancement of industrial integration. Promoting the high-quality development of rural areas and accelerating the participation of farmers in all spheres of the digital economy, life, and ecology while deploying rural digital infrastructure construction in accordance with local conditions [28] (pp. 21–35) is a crucial means of accelerating the digital empowerment effect. Furthermore, the digital hard and soft environments have significantly advanced and transformed the rural development model, which constitutes a substantial area of inquiry and application in the realm of digital village construction.

(3) The "feedback" effect: Promoting the government's financial tax revenue increase, improvement in the rural public service system, and the construction of a beautiful countryside, the rural inclusive green growth development model can reduce the cost of environmental pollution remediation, thereby mitigating the issues of inadequate funds for rural digital infrastructure construction, the lack of digital participation among farmers, and the challenge of the sustainable development paradigm [29] (pp. 113–135). The feedback mechanism is as follows: "Digital village construction–rural inclusive green growth–digital village construction".

Based on the above analysis, we propose the hypothesis that the construction of digital villages is coupled and coordinated with inclusive green growth in villages (Figure 1).

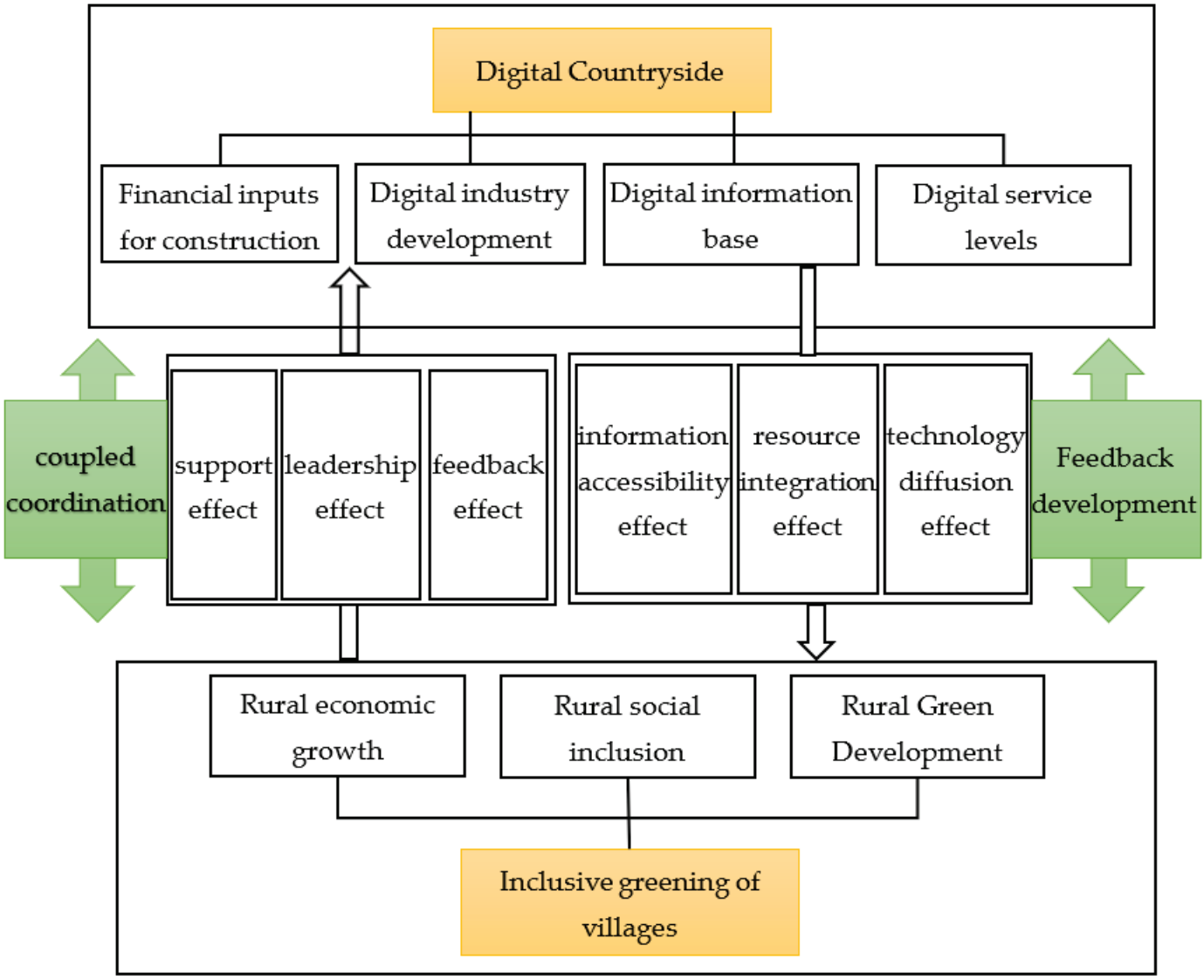



**Figure 1.** The mechanism diagram of coupling coordination between digital village construction and rural inclusive green growth.

## 3. Research Design

### *3.1. Construction of an Evaluation Indicator System for Digital Village Construction and Inclusive Green Rural Growth*

#### 3.1.1. Level of Development of Digital Villages

In this study, we selected the most influential and dominant indicators from an input–output perspective to construct the measurement system (Table 1). This selection was based on the research results of existing scholars [30,31] (pp. 21–33, pp. 101–111) and the Digital Village Development Action Plan (2022–2025), as well as on other policy documents and references. The measurement system is constructed using the Digital Village Construction Guide 2.0 and other relevant policy documents. Because land resources are relatively fixed in nature, they are primarily expressed in terms of labor, technology, and capital when constructing the input indicators and in terms of rural digital industry development when constructing the output indicators.

**Table 1.** Evaluation indicators for digital village development.

| Level 1 Indicators | Secondary Indicators | Interpretation of Secondary Indicators |
|---|---|---|
| Financial inputs for construction | Investment in agricultural production | Investment in fixed assets in agriculture, forestry, and fisheries |
| | Financial investment in agriculture | Balance of agriculture-related loans |
| | Investments in information technology applications such as the Internet of Things | Fixed asset investment in rural transport, storage and postal services |
| Digital industry development | digital base | Number of Taobao villages |
| | Level of digital transactions | E-commerce sales and purchases |
| | Level of network payments | Digital Index of Rural Financial Inclusion |
| | Smartphone penetration rate | Rural year-end mobile phone ownership per million households |
| Digital information base | Computer penetration rate | Rural year-end computer ownership per million households |
| | Radio and television penetration | Rural cable broadcasting and television penetration rate |
| | Internet penetration | Number of rural Internet broadband access subscribers |
| | Agro-meteorological observatories | Rural meteorological observation operations |
| Digital service levels | Scope of services for information technology applications such as the Internet of Things | Rural delivery routes |
| | Digital Talent Service Workforce | Agricultural technicians |
| | Level of consumption of digital services | Consumption expenditure on transport and communications per rural household |

The provision of construction capital input serves as the fundamental economic underpinning for rural development. In accordance with the research of Zhu Honggen and Chen Hui [30] (pp. 21–33) and Yin Haodong et al. [32] (pp. 48–56), construction capital investment was chosen to represent the investment in digital rural development. Specifically, investments in information technology applications such as the Internet of Things, agricultural production investment, and agriculture-related financial investment were considered. The foundation of assessing the establishment of digital villages lies in the progress of digital industry. To this end, the Action Plan for the Development of Digital Villages (2022–2025), the Guidelines for the Construction of Digital Villages 2.0, and the No.1 Document of the Central Government in 2023 all unequivocally advocate for the promotion of the "digital commerce and agricultural development" strategy and the "vigorous development of e-commerce of agricultural products". As a result, the digital base, digital transaction level, and online payment level were the primary metrics utilized in this study. The digital information base serves as the technological foundation for progress, encompassing livelihoods as well as production. As a consequence, in this study, we made use of the findings of Fei Wang et al. [33] (pp. 122–143) to assess the penetration of agro-meteorological observation stations, smartphones, computers, radio, television, and the Internet. The digital service level is the exogenous force of development, and the Outline of Digital Rural Development Strategy emphasizes the need to reinforce talent support, among other things, and accelerate digital technology adoption in order to empower rural production and life. Consequently, we evaluated the level of digital service consumption, the digital talent service team, and the service scope of information technology applications such as the Internet of Things in accordance with the findings of Zhu Honggen and Chen Hui [30] (pp. 21–33).

3.1.2. Level of Inclusive Green Rural Development

The indicator system construction method and the data inclusion analysis method are the primary determinants of inclusive green growth measurement. However, the data inclusion analysis method measures the process of transforming the input factors into output factors, which is not suitable for the inclusive green growth investigated in this study. Hence, we employ the indicator system construction approach, grounded in the framework of development economics. Drawing inspiration from the scholarly consensus regarding inclusive green growth, which characterizes it as a coordinated development process encompassing the economy, society, and environment dimensions [2] (pp. 3–20) and the accessibility of indicator data, it is recommended that assessment indicator systems for rural inclusive green growth be constructed using the three dimensions of rural economic growth (Table 2). Regarding the aspect of rural economic development, the 2023 Central Rural Work Conference underscored the importance of integrating a double-cycle strategy that consciously incorporates efficiency and quality improvements. Hence, in consideration of the research conducted by Ji Zhiheng [34] (pp. 25–44) and Liu, Z.Y. and Zhe Vakas [35] (pp. 28–44), we selected labor productivity and land productivity as indicators of rural economic growth efficiency. The proportion of GDP attributable to the primary sector, the degree of agricultural mechanization, and the disposable income per capita of rural inhabitants were chosen as the indicators of the rural economy expansion potential. To assess the rural external trade and domestic consumption capacities, the agricultural product market turnover as a percentage of the primary production value and the proportion of consumer good retail sales in settlements and rural areas as a percentage of the total consumer good retail sales were chosen as indicators. Regarding the aspect of rural social inclusion, the 2023 Central Economic Conference underscored the importance of "concentrating on high-quality development, efficiently protecting and enhancing people's livelihoods, with the ultimate goal of ensuring that the benefits of development increasingly and equitably benefit all individuals' livelihoods in order to strengthen the level of livelihood protection". In this study, we selected the urban–rural income gap, village health rooms, rural hospitals, health workers, rural cultural stations, number of rural old-age pension service organizations, expenditure on the rural minimum subsistence guarantee, number of rural residents with minimum subsistence guarantees, average level of education, number of participants in pension insurance, and number of participants in health insurance by combining the rural characteristics and referencing the works of Liu Chengkun and Zhang Minghong et al. [36] (pp. 1–7) and Xu Xue and Wang Yongyu [37] (pp. 64–83). The Strategic Plan for Rural Revitalization (2018–2022) explicitly specifies that in the context of green rural development, agricultural and rural habitat improvement and the acceleration of green development should be prioritized, which entails the implementation of green production methods and the establishment of green living environments. Hence, this research draws inspiration from the investigations conducted by Jia Jin et al. [38] (pp. 70–82) and Yan Zhoufu and Wu Fangwei [39] (pp. 90–103), which assessed the greening of rural life through indicators such as the forest coverage, number of public toilets, and rate of harmless domestic waste treatment. The greening of rural production was quantified through the proportion of model counties dedicated to recreational agriculture, the intensity of the fertilizer and pesticide application, and the intensity of the forest coverage.

**Table 2.** Rural inclusive green growth indicator construction.

| Level-1 Indicators | Secondary Indicators | Interpretation of Secondary Indicators |
|---|---|---|
| Rural economic growth | Land productivity | Gross agricultural output/area sown under crops |
| | Labor productivity | Gross output value of agriculture, forestry, animal husbandry, and fishery/number of persons employed in the primary sector |
| | Percentage of agricultural economics | Primary sector as a percentage of GDP |
| | Level of agricultural mechanization | Total power of agricultural mechanization level |
| | Per capita disposable income of rural residents | Gross disposable income per rural inhabitant/population of rural inhabitants |
| | Foreign trade | Agricultural market turnover/value of primary production |
| | Rural consumption levels | Share of retail sales of consumer goods in townships and rural areas in total retail sales of consumer goods |
| Rural social inclusion | Urban-rural income gap | Average income of urban residents/average income of rural residents |
| | Village health offices | Number of rural health centers |
| | Rural hospitals and health workers | Number of rural hospitals and health personnel |
| | Rural Cultural Stations | Total number of cultural stations established in rural areas |
| | Number of rural elderly services | Number of institutions established in rural areas specializing in the provision of elderly services |
| | Expenditure on rural minimum subsistence guarantee | Expenditure on funds corresponding to the minimum subsistence level provided by the government to ensure the basic livelihood of rural low-income families |
| | Number of rural residents guaranteed minimum subsistence allowance | Number of people eligible for the rural minimum subsistence guarantee who are eligible to receive the minimum subsistence guarantee provided by the government |
| | Average rural educational attainment | Average level of education of people living in rural areas |
| | Number of pension insurance participants | Number of pension insurance participants for the year |
| | Number of participants in medical insurance | Number of persons enrolled in health insurance during the year |
| Rural green development | Percentage of model counties for leisure agriculture | Number of leisure agriculture demonstration counties as a proportion of the total number of counties and districts |
| | Green Food Certification Index | Green food back in the day |
| | Fertilizer intensity | Fertilizer use/cultivated land area |
| | Pesticide Intensity | Pesticide use/cultivated land area |
| | Intensity of agricultural plastic film use | Agricultural plastic film use/cultivated land area |
| | Forest Coverage | Forest cover |
| | Soil erosion control area | Soil erosion control area |
| | Number of public toilets | Total number of toilets for public use |
| | Harmless treatment rate of domestic waste | Non-hazardous domestic waste disposal rate |

### *3.2. Coupled Coordination Degree Model*

The coordinated relationship between systems that foster one another is referred to as coupling [40] (pp. 72–90). Coupling denotes the synergistic development that results from the interactions and influences between systems. The model's extensive application within the economic domain underscores its notable degree of rationality. An investigation

was conducted to examine the correlation between rural inclusive green growth and digital villages through the development of a coupling model of the two:

$$C_{t,i} = \sqrt{\frac{DE_{t,i} \times DF_{t,i}}{\left(\frac{DE_{t,i} + DF_{t,i}}{2}\right)^2}} \quad (1)$$

The coupling degrees between the Digital Rural Development Index ($DE_{t,i}$) and the Rural Inclusive Green Growth Index ($DF_{t,i}$) for region i in year t are denoted by $C_{t,i}$. Before the coupling can be calculated, the values of these indices must be normalized and shifted due to their numerical differences. The coupling index quantifies the degree of interdependence between inclusive green rural growth and digital village development, ranging from 0 to 1. A lesser value indicates that the progress of both entities is hindered and disorderly; conversely, a greater value signifies that the two entities foster one another and are advancing in unison.

Nevertheless, it is challenging to precisely ascertain the coupling degree between the particular digital village and rural inclusive green growth development levels. The coupling degree (C) is 1 when DE = DF. In the event that the two indices exhibit similarity, the coupling degree remains high despite their low development rates. Hence, to conduct a thorough evaluation of the degree of coordination and development of rural inclusive green growth and digital villages, in this article, we employ a coupling coordination degree model, drawing inspiration from the research conducted by Zhu et al. [30] (pp. 21–33), Pi, Jiancai and Song, Daqiang [40] (pp. 72–90), and Liu, Tan et al. [41] (pp. 1–36):

$$T_{t,i} = \alpha DE_{t,i} + \beta DF_{t,i} \quad (2)$$

$$D_{t,i} = \sqrt{C_{t,i} \times T_{t,i}} \quad (3)$$

The rural inclusive green growth and digital village coupled coordination degree ($D_{t,i}$) value ranges from 0 to 1, with greater values signifying enhanced coordination between them and lower values signifying the opposite. The combined development level of the two is represented by the comprehensive evaluation index ($T_{t,i}$), wherein $\alpha$ and $\beta$ represent the contribution of digital communities to rural inclusive green growth, respectively, and $\alpha + \beta = 1$. In this study, the equal importance of both variables was assumed, denoted as $\alpha = \beta = 0.5$. The relationship between rural inclusive green growth and digital villages can be described as follows: if $DE - DF > 0.1$, digital villages are surpassing rural inclusive green growth in terms of development; if $DF - DE > 0.1$, digital villages are falling behind rural inclusive green growth; and if $DE - DF \leq 0.1$, the two are at more comparable levels of development. Drawing inspiration from the research conducted by Liu Chunyu et al. [42] (pp. 1–14) and Tan Juntao et al. [43] (pp. 3827–3834), in this study, we categorized the degrees of coupling coordination between rural inclusive green growth and digital village development into four distinct classifications (Table 3).

**Table 3.** Coupling coordination metrics and types.

| Type of Coupled Coordination | Low Coupling Coordination | Moderate Coupling Coordination | Highly Coupled Coordination | Extreme Coupling Coordination |
|---|---|---|---|---|
| D-value interval | $0 < D \leq 0.3$ | $0.3 < D \leq 0.5$ | $0.5 < D \leq 0.8$ | $0.8 < D \leq 1$ |

Digital villages and inclusive green growth may be related, according to a comprehensive analysis of multiple indices. In this study, we calculated the digital village and rural inclusive green growth coupled coordination degrees at the provincial level in China from 2011 to 2021 using Equations (2) and (3), as shown in Appendix A. The digital village and

rural inclusive green growth coupled coordination degrees were examined in greater detail using the coupled coordination degree model.

### *3.3. Modified Coupled Coherence Model*

To enhance the rigor of the research content presented in this article, a robustness test was performed. Equation (3) states that the coupled coordination degree model will be simplified in the previous iteration when the combined contribution of rural inclusive green growth and digital villages is 0.5:

$$D_{t,i} = \sqrt[4]{DE_{t,i} \times DF_{t,i}} \tag{4}$$

Implementing this simplification could potentially compromise the model's validity. Therefore, Shujia Wang et al. [44] (pp. 793–810) proposed a modified coupled model that can effectively resolve this issue:

When $DE_{t,i} > DF_{t,i}$,

$$C'_{t,i} = \sqrt{[1 - (DE_{t,i} - DF_{t,i})] \times \frac{DF_{t,i}}{DE_{t,i}}} \tag{5}$$

When $DE_{t,i} < DF_{t,i}$,

$$C'_{t,i} = \sqrt{[1 - (DF_{t,i} - DE_{t,i})] \times \frac{DE_{t,i}}{DF_{t,i}}} \tag{6}$$

Appendix B presents the updated linked coordination of digital villages and rural inclusive green growth at the provincial level in China for the period of 2011–2021, derived from a thorough investigation of the indicators and Equations (5) and (6).

## 4. Results and Interpretations

### *4.1. Modified Coupled Coherence Model*

Figure 2 shows that, when looking at China as a whole, the average value of the Digital Village Index since 2011 has demonstrated an increasing trend annually. This is a result of the 2012 introduction of the "digital transformation" concept; the building of digital infrastructure and the encouragement of the use of Internet technology; the creation of national strategies like "Broadband China", "Internet Plus", and "big data"; as well as the quick advancement of information technology construction. A number of technological advancements in the field of digital technology, including software, electronic information, and communication networks, have continued to support the development of the Internet ecosystem and the ongoing digital infrastructure modernization under the policy's guidance. In order to accomplish the digital transformation of rural areas, China is also actively promoting the digital village strategy, which entails the integration of digital technology into rural economic and social development and improvement in the digital literacy of farmers. Additionally, the Rural Inclusive Green Development Index has exhibited a consistent annual development pattern, albeit with intermittent variations, which is due to the firmly established political system in China. China's strategic decision to "vigorously promote the construction of an ecological civilization" was announced in 2011, and since then, the green concept has emerged as the guiding principle of future development. In terms of development growth rate, the growth rate of the Digital Countryside Index from 2011 to 2021 shows a downward and then upward trend, while the Rural Inclusive Green Development Index generally maintains stability, slowly meandering upward. In 2014, there was a negative growth rate of rural inclusive green development. On the whole, the growth rate of digital village development is greater than rural inclusive green growth. In the past three years, the growth rate of digital villages has been maintained at around 10%, while rural inclusive green growth has been maintained at around 5%. The primary

rationale for this phenomenon is that once digital villages and rural green inclusiveness reach a specific stage of development, additional progress becomes impracticable, resulting in a marginal deceleration in their respective growth rates. This signifies that China's digital villages and rural green inclusiveness are gradually transitioning from an initial stage of immature development to one of stability.

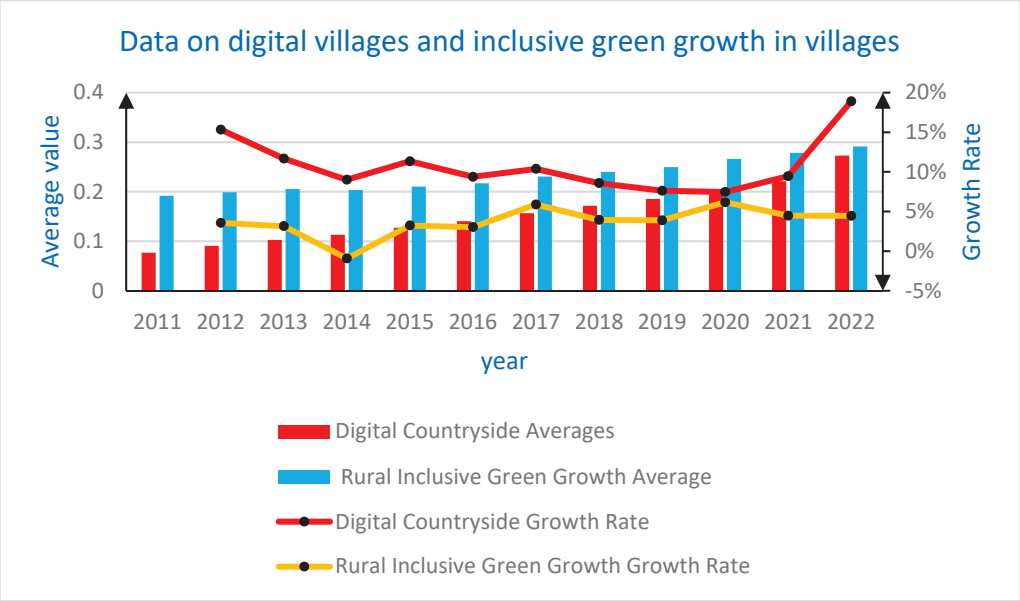



**Figure 2.** Mean and growth rate of the Provincial Digital Village Index and the Rural Inclusive Green Growth Index, 2011–2021. (The horizontal axis represents the year, and the vertical axis represents the numerical value).

As illustrated in Figure 3, the index trends across all regions are essentially the same: upward. It is noteworthy to mention that while both inclusive rural development and digital village development exhibit considerable regional variation, they are fundamentally distinct. "Diminishing from east to west" is the degree of digital village development; the eastern and central regions have considerably more developed digital villages than the western region. When considering the digital countryside expansion rate, it is noteworthy that the eastern region has maintained a commendable degree of digitalization throughout the entire time span. Although the central and western regions are experiencing some growth, it is evident that their overall levels of development are lagging. An exhaustive examination reveals that, in terms of digital village development, the eastern region is at the forefront, with the central region following suit, whereas the western region is falling behind. This is a result of the east's stronger innovation capacity and economic foundation, as well as its more rapid digital technology advancement. Additionally, technological spillovers from the east and comparatively stronger economic conditions in the central region could prove advantageous. In contrast, the western region's comparatively low economic development level and inadequate investment in digital infrastructure development and maintenance render it relatively weak. "Green inclusive development in rural areas is greatest in the center, second greatest in the east, and least in the west".

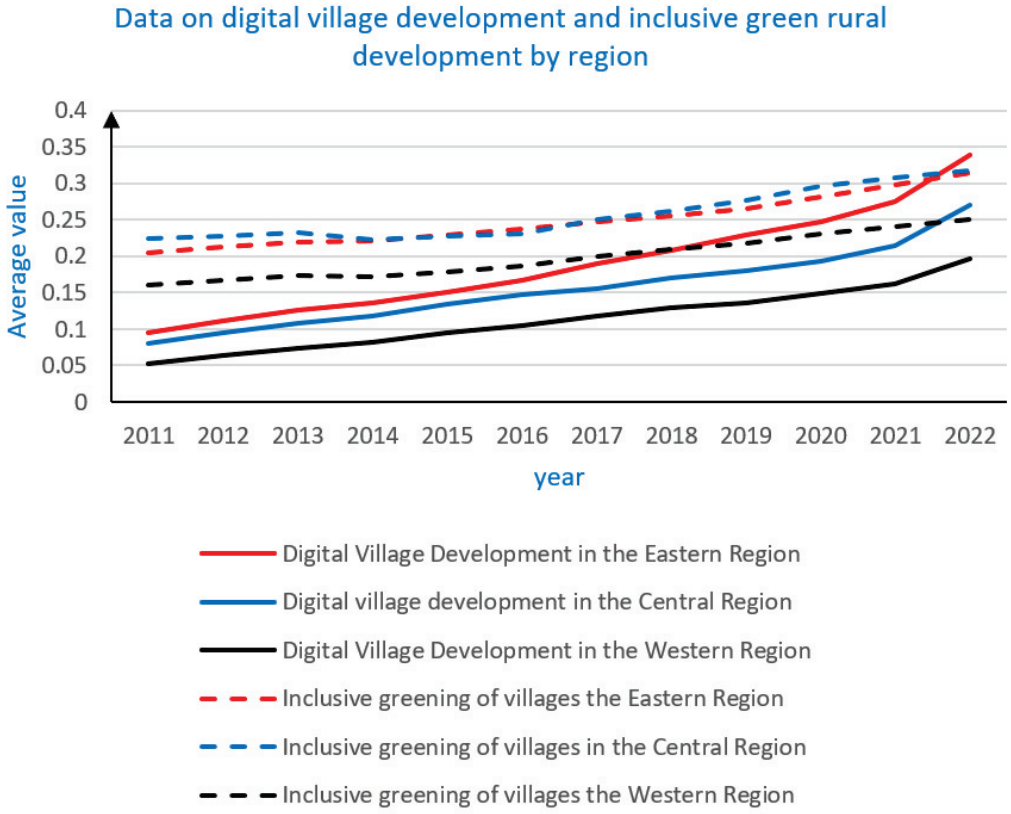



**Figure 3.** Digital rural development and rural inclusive green development means by region, 2011–2021. (The horizontal axis represents the year, and the vertical axis represents the numerical value).

For a more comprehensive examination of the factors contributing to the variability observed in inclusive green rural development, the twelve-year averages of the Level-1 indicators from the Digital Rural Inclusive Green Development Index for every region from 2011 to 2022 are displayed in Figure 4. It is evident that the rural green development indicator exhibits minimal variation among the three regions. The eastern region exhibits a superior level of rural economic development in comparison to the central and western regions. Conversely, the central region surpasses the eastern and western regions by a significant margin in the rural social inclusion indicator. China's balanced regional development strategies, exemplified by the "Rise of Central China" and "Western Development" policies, have yielded favorable outcomes for the central region. Notably, increased resource investment and government attention have been directed towards rural revitalization and ecological development. Furthermore, as a result of its comparatively advantageous natural circumstances, the central region has prioritized sustainable development models and green agriculture, including eco-tourism and rural tourism, in order to further encourage inclusive green growth in rural regions. Although the eastern region is experiencing more rapid economic development, its focus is primarily on urban and coastal areas. Although rural regions do benefit from economic spillovers, there may still be disparities in the social inclusiveness between urban and rural areas, particularly in education, healthcare, and social services. In contrast, the western region is afflicted by more severe environmental challenges, including desertification and drought, in addition to infrastructure deficiencies that hinder the rate and caliber of its rural inclusive green expansion.

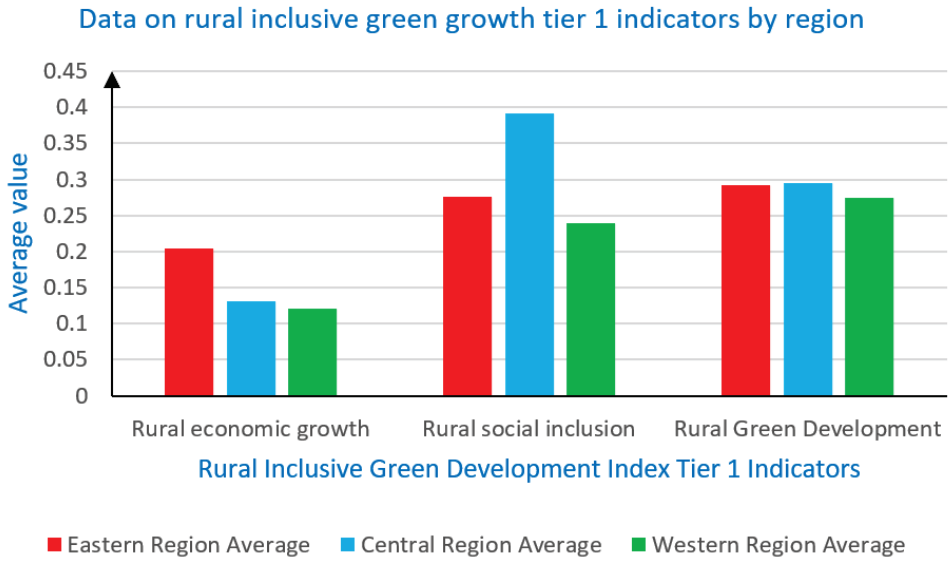



**Figure 4.** Digital rural development and rural inclusive green development means by region, 2011–2021. (The horizontal axis represents the specific classification of inclusive green development, while the vertical axis represents numerical values.)

### *4.2. Time-Series Evolution of the Coupled Coordination Degree of Digital Villages and Inclusive Rural Green Growth*

The digital village and rural inclusive green growth coupling coordination degrees from 2011 to 2022 were assessed using the evaluation index system of digital villages and rural inclusive green growth, which was established previously and is based on the coupling degree and coupling coordination degree model (Appendix A). Based on the data presented in Appendix A, the digital village and rural inclusive green development coupling coordination degrees in 30 provinces of China have been predominantly between 0.20 and 0.75 over the past decade. The average coupling coordination degree of China's rural inclusive green growth and digital countryside was 0.5072% in 2021, representing a high coupling coordination level. From 2011 to 2021, the mean coupling coordination degree of China's rural inclusive green growth and digital countryside was situated at the moderate coupling level. In contrast to the full sample period from 2011 to 2022, during which the coupling coordination between the two indices was estimated to have a mean value of 0.4209, the coupling coordination between them was below the mean value for the subsequent six years. A steady growth was observed in the chronological evolution of digital villages and inclusive rural green growth between 2011 and 2016, which may have been facilitated by proactive policy orientation, infrastructure development, and social participation. However, China's rural areas underwent uneven development during this time, with some regions presumably receiving more attention and inputs than others, resulting in their overall underdevelopment. The implementation of strategies such as "Digital China" and "Rural Revitalization" has increased the government's support for rural digitalization, including policy guidance, financial investment, and project support. This has facilitated the deep integration of digital technology and rural development, resulting in a rapid increase in coordination during the rapid development phase (2016–2021). This demonstrates that China has consistently augmented the input provision for inclusive development and digitalization, rationalizing the input–output structure of the two systems. The advancement of ecological environmental protection has accompanied the development of the digital countryside, and the coupling between the two has been significantly improved.

The adjustment of the Chinese mean for the coupled harmonization of the digital countryside and rural inclusive green development indices is dependent on the year 2013 with respect to the leading or lagging relationship between their development. The advancement of digital villages fell behind the comprehensive green expansion of rural regions from 2011

to 2013 (type a) due to the fact that the majority of China's rural areas had not yet developed a robust Internet infrastructure at this time. Inadequate network coverage hindered the access to, distribution of, and utilization of digital information. Consequently, rural inhabitants were unable to fully benefit from digital resources and services. Furthermore, the adoption and integration of new technologies were impeded by traditional ways of life and attitudes. The inadequate provision of network coverage in rural regions has resulted in the restricted availability and utilization of digital information, impeding residents' ability to fully benefit from digital services and resources. Digital Villages and Rural Inclusive Green Growth in Synergy since 2014 (type c) indicates that digital villages and inclusive green rural development are, on the whole, becoming progressively more supportive and mutually reinforcing. From 2011 to 2013, digital village development lagged behind rural inclusive green growth (type a). However, from 2013 onwards, digital village development and rural inclusive green growth have developed synergistically (type c), which indicates that, since 2011, digital villages have expanded at a faster rate than rural inclusive green growth, reflecting a transition from pioneering to adaptive and synergistic development. This is due to the delayed emergence of digital villages, whereas rural inclusive development was promoted and implemented to some degree from 2011 to 2013, thereby establishing a foundation. Digital village promotion may have been hampered in its infancy by a variety of obstacles, including technological preparedness challenges, infrastructure development obstacles, and so forth. As a result, the development of digital villages has lagged behind that of inclusive green rural growth. Nevertheless, as time has progressed, the notion of digital villages has garnered traction, policy backing has been established, and technological advancements have developed, fostering synergies between digital villages and inclusive rural green growth. The swift assimilation of digital communities subsequent to 2013 can be ascribed to the expeditious advancement of digital technologies, more profound policy execution, and the broader societal approval of digitalization. The transition from inclusive green rural growth surpassing digital villages to their tandem development signifies the progressive integration of digitalization into rural development and the gradual establishment of a virtuous cycle wherein the advancements of digital villages and inclusive green rural growth are supportive and mutually reinforcing.

The validation of the revised coupling model revealed that it substantially enhanced the coupling's discriminatory and usage validity (see Appendix B). The coupling coordination degree outcomes computed using this model indicate that, as depicted in Figure 5, the values of the coupling coordination degrees between digital villages and rural inclusive green growth in provincial-level regions of China have decreased. However, this has not altered the trajectory of the coupling coordination degree development in each province and city; in fact, this result is essentially identical to previous empirical findings, and it continues to hold true. The modified coupled model performed admirably on the robustness test. The mean coupling coordination between the modified digital village and rural inclusive green development indices in China is 0.3684, with a mean coupling coordination value range between 0.15 and 0.65, indicating a moderate level of coordination.

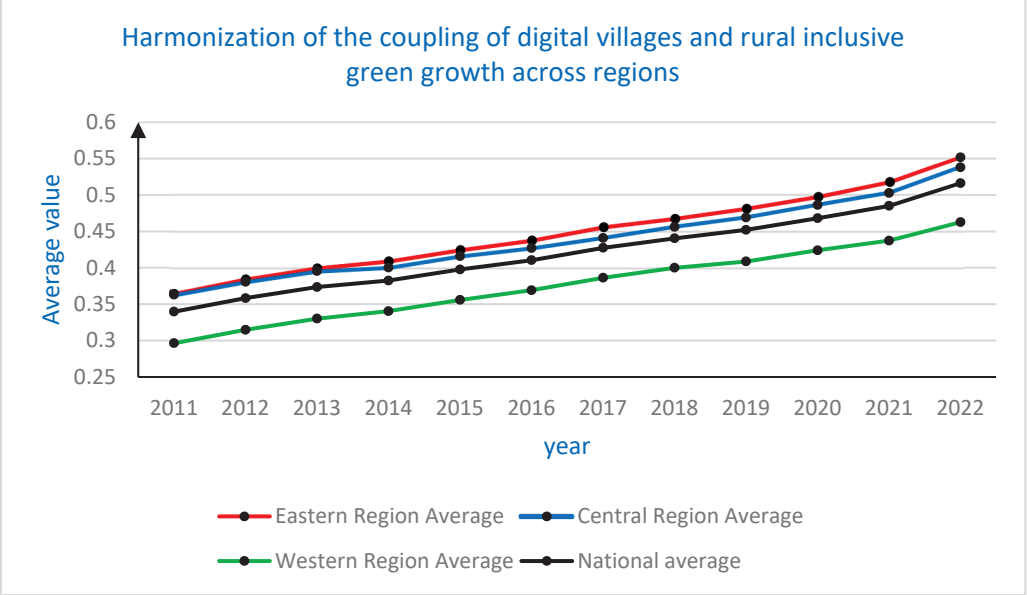



**Figure 5.** Harmonization of the coupling of digital villages and inclusive green growth in villages by region, 2011–2021. (The horizontal axis represents the year, and the vertical axis represents the numerical value).

### *4.3. Spatial Evolution of the Coupled Coordination Degree of Digital Villages and Rural Inclusive Green Growth*

In order to conduct a more comprehensive spatial comparison of the provinces and to fully account for the results of the digital village and rural inclusive green growth time-series evolution analysis, in this study, we evaluated the coupling coordination degree of each province of China using three time points: 2011, 2016, and 2021. We utilized ArcGIS 10.8 to map the spatial differentiation with an emphasis on depicting the coupling coordination level and corrected coupling coordination level for each province and city and displaying these data through the use of color differentiation.

As depicted in Figure 6, the coupling coordination degree trends are essentially the same across all regions at the regional level; each region experiences an annual increase. Nevertheless, the eastern region has the most pronounced coupling coordination degree, followed by the central region, whereas it is the least pronounced in the western region. Furthermore, while the central and eastern regions exhibit coordination degrees that surpass the Chinese average, that of the western region remains significantly divergent from the Chinese average. The eastern region had already attained a coupling coordination degree value of 0.4 as of 2013, signifying that, by 2022, it had successfully transitioned from a state in which digital rural development lagged behind rural inclusive green growth (type a) to one in which the two advance synergistically (type c). In contrast, the center achieves synergy between the two in 2015 (type c), while the west completes the transition in 2014. As of the year 2022, the coupling coordination degree in the eastern region was 0.5516, while it was 0.5379 in the central region and 0.4627 in the western region. It is noteworthy that while digital country-side development in the central region falls behind rural inclusive green development, the level of integration and coordination between the two is greater than in the eastern region. One potential explanation for this discrepancy is that while the average rate of rural economic growth in the central region is comparatively lower than that in the eastern region, it offers specific benefits in terms of promoting rural social inclusion and facilitating sustainable development in the countryside. Conversely, the eastern region's rapid economic growth may give rise to challenges such as environmental pollution and resource overexploitation, despite its more developed technological and information infrastructures. Furthermore, in contrast to the central region's sluggish economic development, the establishment of digital villages commenced belatedly and progressed at a sluggish

rate. However, in promoting inclusive green rural development, the central region may have adopted more proactive and adaptable strategies, such as emphasizing ecological preservation and promoting green agriculture, which has assisted in enhancing its coupling coordination. Moreover, as part of the regional coordinated development strategy of the Chinese government, additional policy support and resource allocation may have been directed toward the promotion of rural green growth and digitalization in the central region, facilitating improved coupling coordination between digital village construction and inclusive rural green development in this area. Nevertheless, the central region faces obstacles such as an inadequate support capacity for fundamental digitalization, a weak foundation in the digital technology industry, and a scarcity of human resources. As a result, the progress of digital countryside construction has been impeded by the developed eastern regions, perpetually falling behind that of rural inclusive green development. Consequently, despite the eastern region having a lower degree of coupling coordination than the central region, the implementation of digital village construction and inclusive green growth in rural areas has experienced a postponement in their synergistic development.

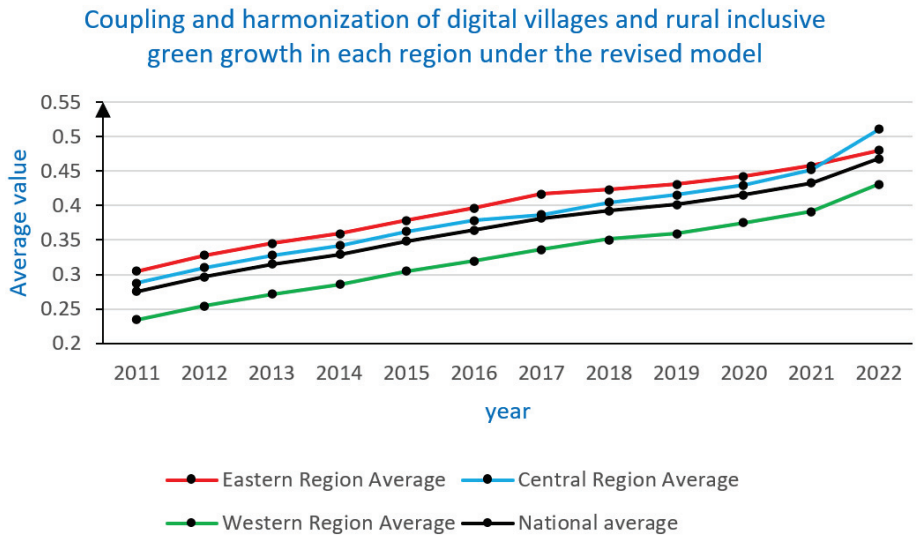



**Figure 6.** Degree of harmonization of the coupling of digital villages and rural inclusive green growth in each region under the revised model, 2011–2021. (The horizontal axis represents the year, and the vertical axis represents the numerical value).

Based on the findings of the time-series analysis examining the digital countryside and rural inclusive green growth coupled coordination degrees (as depicted in Figure 7), the provincial level can be categorized into two stages: Stage I (2011–2016) and Stage II (2017–2022). Figure 7 illustrate the coupling coordination degree and its adjusted values between digital village construction and rural inclusive green growth in various provinces of China for the years 2011, 2016, and 2022. The top three figures depict the temporal and spatial evolution of the coupling coordination degree between digital village construction and rural inclusive green growth. The bottom three figures illustrate the temporal and spatial evolution of the adjusted coupling coordination degree for digital village construction and rural inclusive green growth. Based on the coupling coordination degrees of digital village construction and rural inclusive green growth in 2011, 2016, and 2022, it can be observed that in 2011, most of the eastern and central regions of China were in a state of moderate coupling coordination, while the western regions were mostly in a state of low coupling coordination. By 2016, some provinces in the eastern regions began to reach a state of high coupling coordination, the central regions remained in moderate coupling coordination, and the number of provinces in the western regions with low coupling coordination decreased. Notably, Sichuan Province in the western region advanced to a state of high coupling coordination, benefiting from the Western Development Strategy,

which provided more policies and resources. By 2022, the eastern and southern regions had largely achieved a state of high coupling coordination, and the remaining regions were in a state of moderate coupling coordination. Overall, the coupling coordination degree of digital village construction and rural inclusive green growth in China was at a moderately high level. Based on the adjusted coupling coordination degrees for 2011, 2016, and 2022, it is evident that the overall trend has been one of significant improvement, reflecting the effectiveness of national strategies and investments in promoting digital and green development in rural areas. In 2011, the adjustments show a slight increase in coordination levels, with moderate coordination becoming more widespread. In 2016, the adjustments reflect a substantial rise in high and extreme coordination in the eastern and central regions. By 2022, the adjusted values reveal a significant enhancement in coordination, with high and extreme coordination levels becoming more prevalent across the country. This analysis highlights the consistent upward trend in coupling coordination over time, with significant regional disparities, and the notable progress in economically advanced regions due to stronger economic foundations and better fiscal resources. Significantly, in the year 2018, Zhejiang Province and Guangdong Province underwent a shift from a phase of collaborative development between digital villages and rural inclusive green growth (stage c) to a phase in which digital village development surpassed rural inclusive green growth (stage b). Jiangsu Province also achieved digital village development (stage b) in 2019, which was prior to the achievement of rural inclusive green growth. Zhejiang Province is among the forerunners of the digital economy and e-commerce in China, particularly in urban centers such as Hangzhou. Utilizing its digital economy, Zhejiang Province has actively promoted rural e-commerce and Internet + Agriculture initiatives, thereby facilitating the digital upgrading of the real economy and accelerating the digital transformation of rural areas through the promotion of the Internet's in-depth integration with traditional manufacturing sectors. Guangdong Province, a prominent economic province in China, possesses a robust innovation capacity and an extensive industrial foundation, particularly in the Pearl River Delta area. These attributes furnish favorable circumstances and substantial drive for the digital transformation of rural regions. Constant improvements in the market and consumer demand in rural areas of Guangdong Province as a result of economic growth have fostered the growth of e-commerce and digital services, thereby contributing to the advancement of the digital countryside. Jiangsu Province exhibits a commendable and equitable degree of economic progress. Notably, the disparity in development from the southern to the northern regions of the province has progressively diminished. This progress has prompted the establishment and implementation of digital infrastructure in rural areas and actively advocates for the modernization of agriculture, with a particular emphasis on the advancement of smart agriculture and the utilization of digital technology to enhance the operational effectiveness and product quality. According to a comparative analysis, the spatial aggregation effect of the coupling coordination degrees of the provinces and cities has become more pronounced after eleven years of development. Moreover, the western region exhibits comparatively low coupling coordination degrees, whereas the provinces and cities with high coupling coordination degrees have progressively migrated towards the eastern and central regions.

After modifying the model, the calculated coupling coordination degrees decreased, resulting in a modification to the spatial distribution map. Six provinces and municipalities in China exhibited low coupling coordination levels in 2011, while the remaining provinces and municipalities demonstrated medium coupling coordination levels. Shandong, Jiangsu, Zhejiang, and Guangdong in the eastern region had achieved high coupling coordination degrees by 2016, while Qinghai and Chongqing in the western region had achieved medium coupling coordination degrees. The remaining provinces maintained their current coordination levels. As of 2022, fifty percent of the provinces in the eastern and central regions had achieved high coupling coordination degrees. In contrast, the western region is represented solely by Sichuan Province at a high level of coordination. Hainan and Qinghai continue to operate at low coupling coordination levels, while the remaining

provinces maintain medium coupling coordination levels. The "gradually weakening from east to west" trend remains evident according to the color level differentiation map. Regardless of whether Stage I or Stage II pertains to spatial evolution, Hainan and Qinghai provinces have maintained their low coupling coordination levels despite increases in their coupling coordination degrees; thus, the spatial evolution is relatively minor. In contrast, China's digital countryside and rural inclusive green growth coupling coordination degrees underwent stage changes in the remaining provinces between 2011 and 2022; the spatial evolution is evident, exhibiting greater magnitude in the eastern provinces, while it maintains greater stability in the central and western provinces.

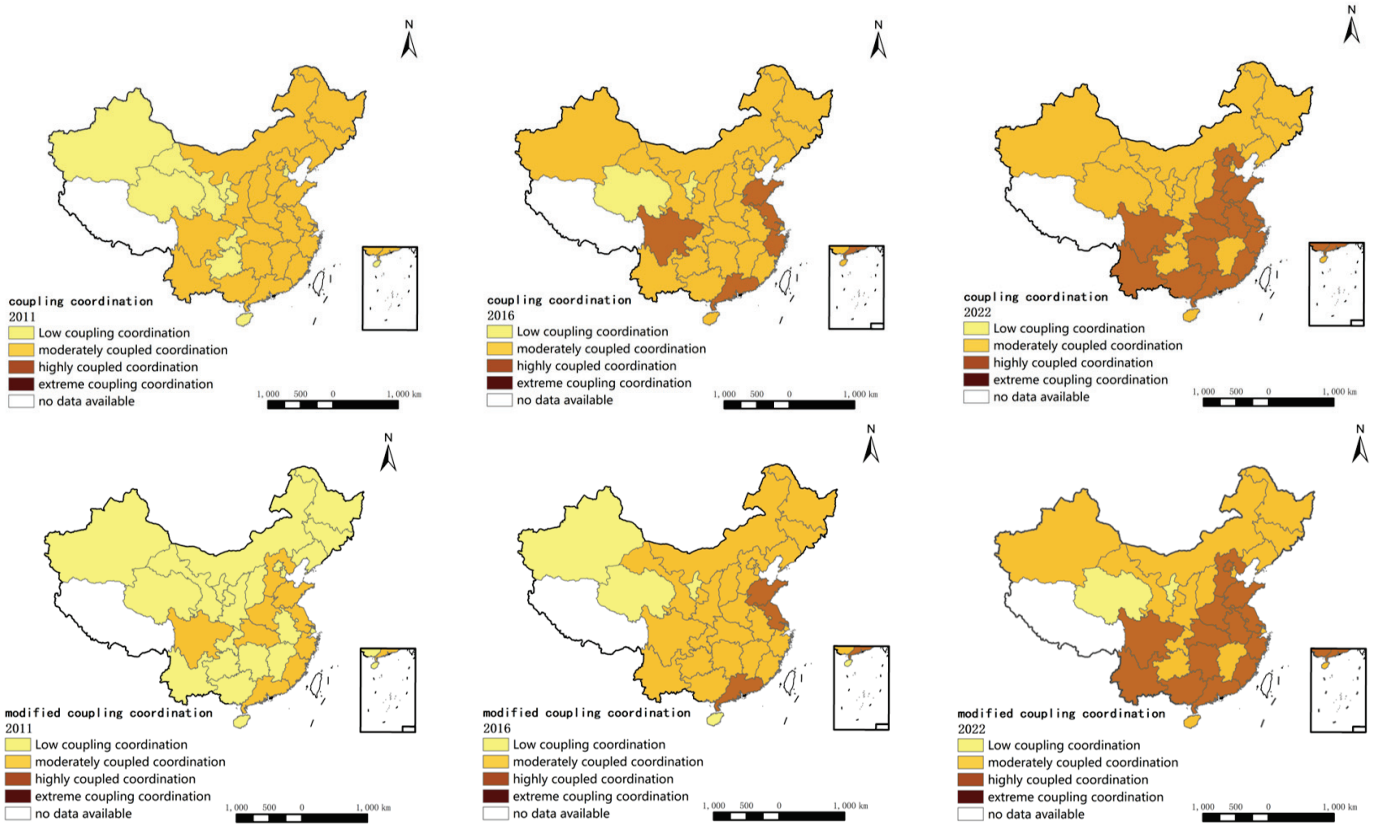



**Figure 7.** The temporal and spatial evolution of coupling coordination degree and its adjusted values between digital village construction and rural inclusive green growth in China (2011, 2016, 2022). Note: Based on standard maps from the Ministry of Natural Resources Standard Map Service website, GS (2023) 2767 (http://211.159.153.75/browse.html?picId=%224o28b0625501ad13015501ad2bfc2187%22, accessed on 16 May 2024), with no modifications to the base map boundaries.

### *4.4. Kernel Density Estimation Results*

The benefits of using kernel density estimation for assessing coupling coordination lie in its ability to smooth data distribution and provide continuous density estimates, thereby making the distribution characteristics of the data clearer and more intuitive. This method can identify potential patterns, peaks, and distribution shapes within the data, aiding in understanding the variations and trends in coupling coordination. Kernel density estimation does not rely on distributional assumptions, making it suitable for various types of data, particularly non-normal distributions, and providing more reliable results. Compared to histograms, kernel density estimation can reveal more distribution details, facilitating a comprehensive analysis of coupling coordination. It also allows for easier comparison of coupling coordination across different regions or time periods, identifying differences and commonalities. Therefore, we constructed a kernel density model to

examine the coupling coordination degree of digital villages and inclusive green growth in rural areas.

Let D be a random variable and $D_1$, $D_2$, ..... $D_n$ be a sample. The kernel density estimate of the probability density function f(x) at any point D can be expressed as:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{D_i - d}{h}\right) \tag{7}$$

In this context, K(·) denotes the kernel function, n represents the sample size, h is the bandwidth, and d indicates the mean. This study employs the Gaussian kernel density function for calculations, which is expressed as:

$$K(d) = \frac{1}{\sqrt{2\Pi}}\exp\left(-\frac{d^2}{2}\right) \tag{8}$$

From 2011 to 2022, the coupling coordination degree in the western region mainly ranged from 0 to 0.6, with peak values concentrated between 0.2 and 0.4. The peaks gradually shifted to the right, indicating a steady improvement in the coupling coordination degree. This reflects the region's continuous enhancement in coordination among various factors, driven by infrastructure development, educational improvements, and national policy support such as the "Belt and Road" initiative (Figure 8).

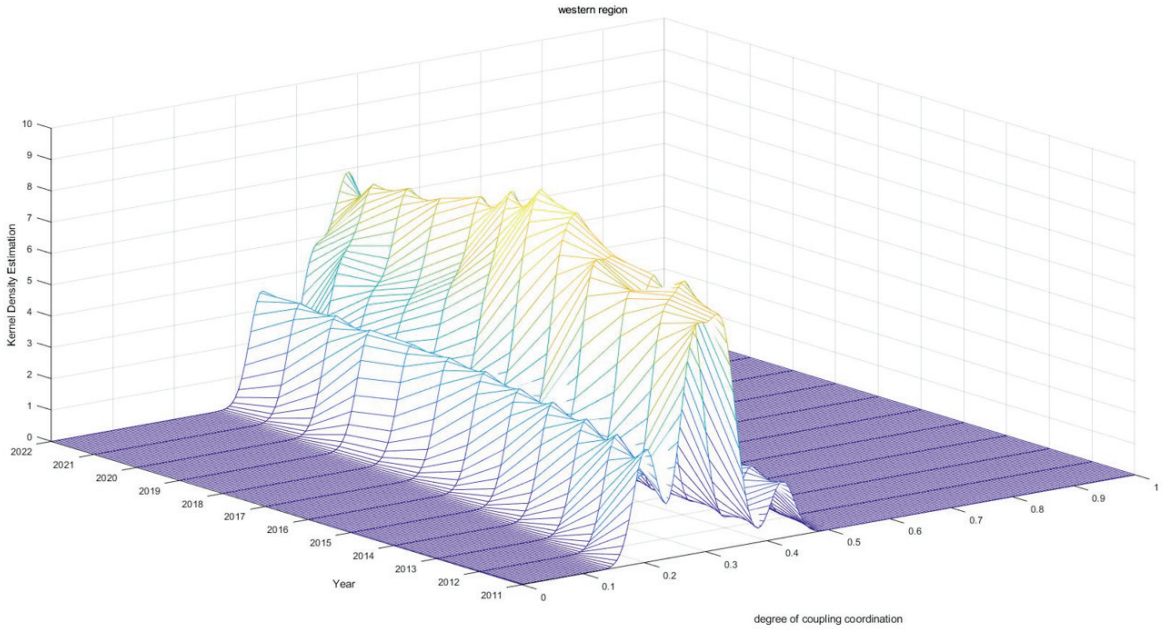



**Figure 8.** Kernel density map of the coupled harmonization of digital village construction and rural inclusive green growth in the western region.

From 2011 to 2022, in the central region, the coupling coordination degree also ranged from 0 to 0.6, with peak values fluctuating significantly between 0.2 and 0.5. The evident multi-peak pattern shows an initial increase followed by a decrease, highlighting the complexity and diversity of industrial restructuring and urbanization processes. This fluctuation is particularly influenced by resource and environmental pressures, as well as economic transitions (Figure 9).

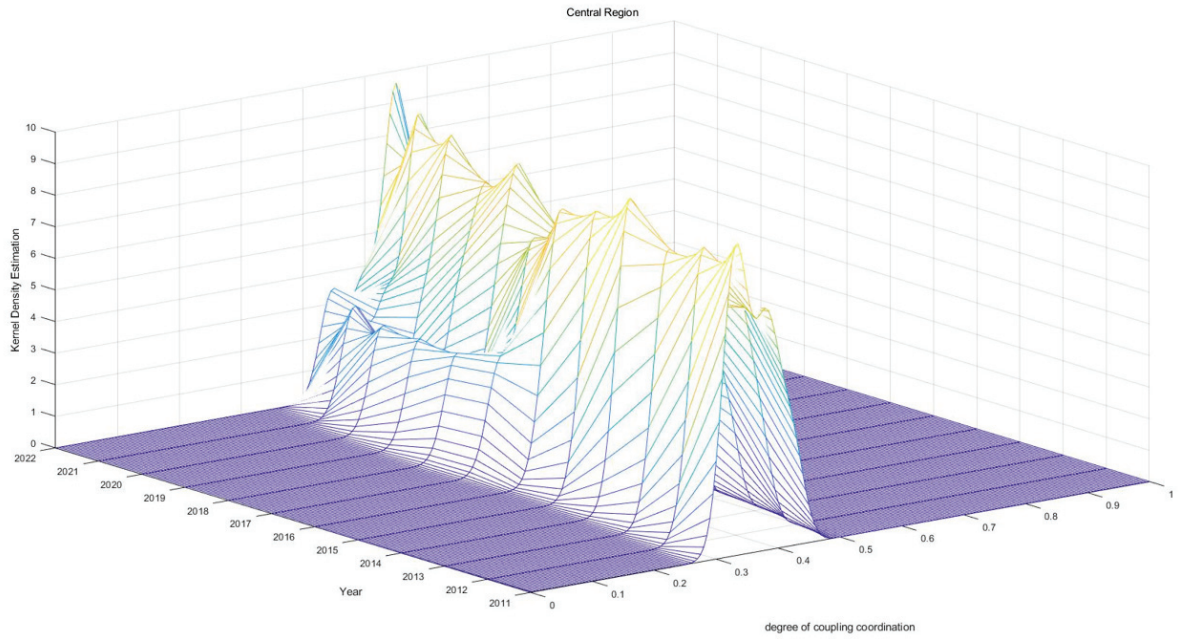



**Figure 9.** Kernel density map of coupled harmonization of digital village construction and rural inclusive green growth in the central region.

From 2011 to 2022, the eastern region's coupling coordination degree was mainly between 0 and 0.5, with peak values concentrated between 0.2 and 0.4. The peaks were narrower and higher, and their number gradually decreased, indicating a trend towards more balanced coordination. This improvement is attributed to the region's industrial upgrading, technological innovation, and sustainable development strategies, demonstrating its strengths in achieving comprehensive coordination (Figure 10).

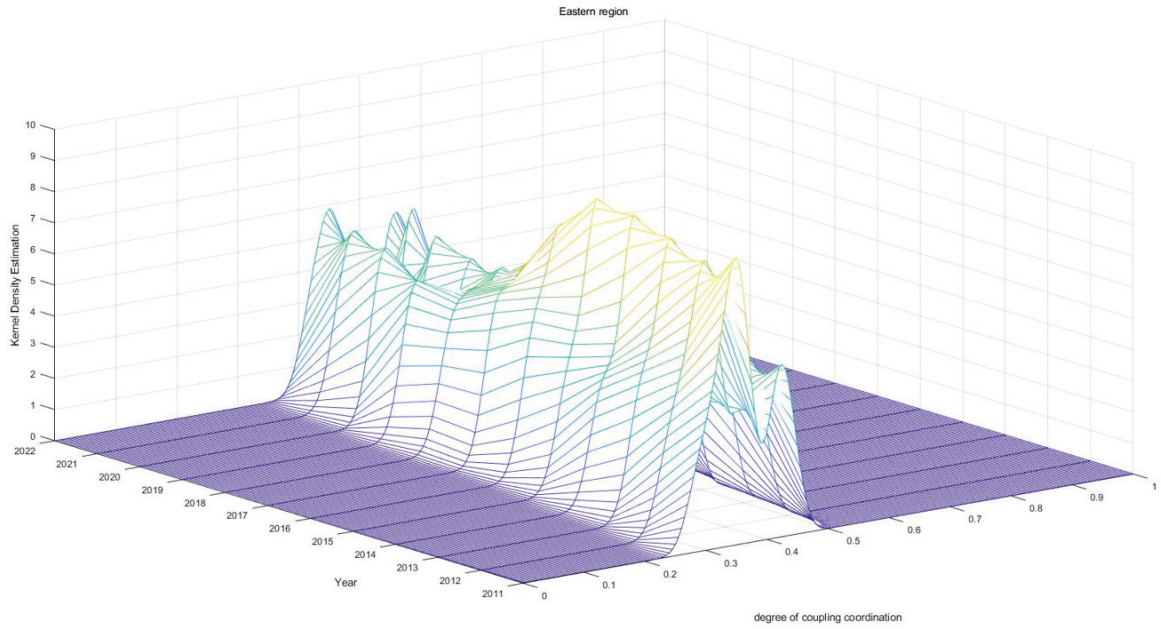



**Figure 10.** Kernel density map of coupled harmonization of digital village construction and rural inclusive green growth in the eastern region.

From 2011 to 2022, overall, across all regions, the coupling coordination degree mainly ranged from 0 to 0.6, with peak values concentrated between 0.2 and 0.5. The moderate fluctuations indicate a gradual improvement in the coupling coordination degree nationwide. This trend reflects the positive impacts of economic reforms, regional coordination development strategies, and the advancement of new urbanization initiatives, leading to enhanced coordination and sustainable development across the country (Figure 11).

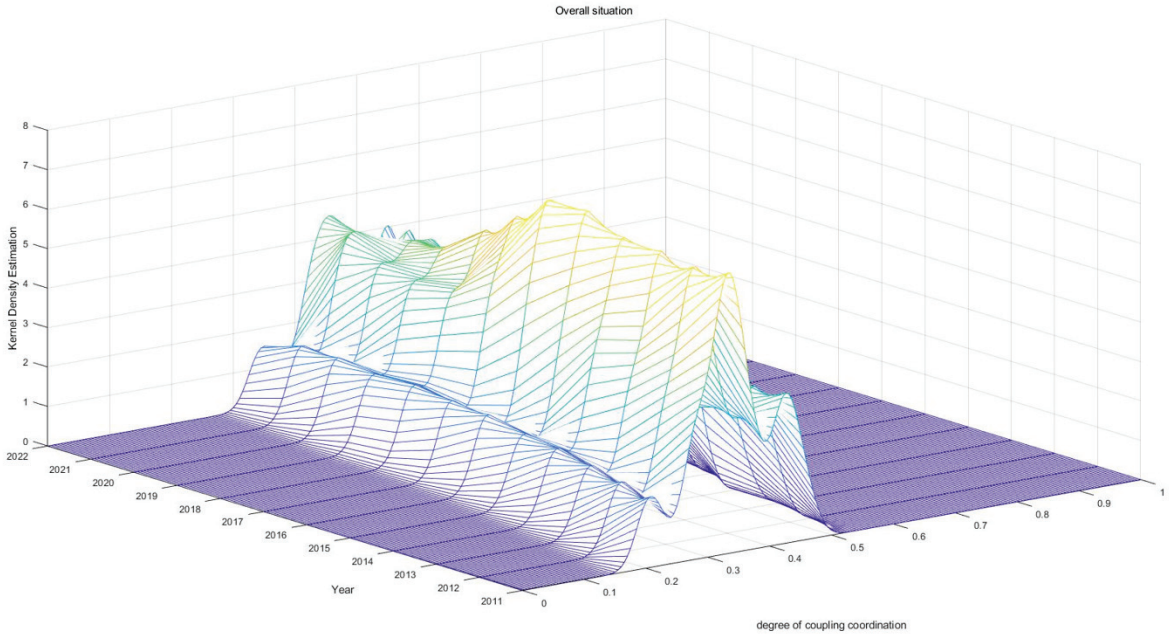



**Figure 11.** Kernel density plot of the coupled harmonization of digital village construction and rural inclusive green growth in China.

### *4.5. Domain-Wide Spatial Correlation Test*

In this study, the Global Moran's I index is utilized to analyze the coupling coordination between digital village construction and inclusive green growth in rural China. Its benefits include revealing spatial autocorrelation, quantifying spatial patterns, detecting and locating clusters of high and low coupling coordination, providing significance testing to ensure the reliability of the analysis results, and offering robust support for policymakers. This helps in formulating precise and effective regional development strategies, thereby promoting coordinated regional development and optimal resource allocation.

Based on the analysis of Moran's I index from 2011 to 2022, the coupling coordination degree in the early period (2011 to 2020) showed an upward trend but did not reach significant levels. This indicates that during these years, the spatial distribution of variables did not exhibit a clear clustering pattern, possibly due to the initial implementation of regional policies, uneven economic development, and incomplete infrastructure development. However, in 2021 and 2022, the Moran's I index increased significantly, indicating notable spatial autocorrelation and a more pronounced clustering of similar values within regions (Table 4). This change can be attributed to the deepening of regional policies, economic restructuring and transformation, improvement of infrastructure, enhanced socioeconomic factors, and policy orientation and resource allocation. These factors have collectively increased spatial dependence and coordination among regions, promoting regional coordinated development and optimized resource allocation.

**Table 4.** Global Moran's I index of the coupled harmonization degree of digital countryside and rural inclusive green growth in China, 2011~2022.

| Year | I | Z | P |
|---|---|---|---|
| 2011 | 0.062 | 0.783 | 0.217 |
| 2012 | 0.069 | 0.837 | 0.201 |
| 2013 | 0.087 | 0.985 | 0.162 |
| 2014 | 0.083 | 0.949 | 0.171 |
| 2015 | 0.089 | 1.004 | 0.158 |
| 2016 | 0.076 | 0.896 | 0.185 |
| 2017 | 0.083 | 0.949 | 0.171 |
| 2018 | 0.114 | 1.202 | 0.115 |
| 2019 | 0.132 | 1.342 | 0.090 |
| 2020 | 0.134 | 1.357 | 0.087 |
| 2021 | 0.180 | 1.731 | 0.042 |
| 2022 | 0.228 | 2.120 | 0.017 |

### *4.6. Analysis of Factors Influencing Coupling Coordination Degree*

Considering the influencing factors of digital rural construction and inclusive green growth in rural areas, this study employs a bidirectional fixed effects model for analysis. The following variables are selected as explanatory variables: (1) urbanization rate, measured by the ratio of urban population to total population; (2) industrial structure, measured by the ratio of the output value of the tertiary industry to that of the secondary industry; (3) innovation level, measured by the natural logarithm of the number of invention patent applications; (4) natural disasters, measured by the ratio of affected area to disaster area; (5) fiscal support for agriculture, measured by the natural logarithm of expenditure on agriculture, forestry, and water affairs; (6) scale of operation, measured by the ratio of grain sown area to total crop sown area; (7) education investment, measured by the ratio of education expenditure to total fiscal expenditure; and (8) environmental investment, measured by the ratio of environmental protection expenditure to total fiscal expenditure.

The coupling and coordination of digital rural construction and inclusive green growth in rural areas are influenced by multiple factors. Here is an explanation of how these eight control variables affect this process (see Table 5):

1. Urbanization Rate: The urbanization rate is an important indicator of the urbanization process in a country or region. As urbanization progresses, rural populations migrate to cities, potentially leading to a reduction in rural labor force, which affects rural economic development and construction. On the other hand, urbanization brings technology and capital to rural areas, promoting the coordinated development of rural construction and green growth.
2. Industrial Structure: Industrial structure refers to the proportion of different industrial sectors in the national economy. The ratio of the tertiary industry (services) to the secondary industry (manufacturing) reflects the level of economic development and structural adjustment. The development of the service industry can diversify the rural economy, reduce dependence on traditional agriculture, and promote green development and rural revitalization.
3. Innovation Level: The innovation level is usually measured by the number of patent applications. An increase in innovation capability can bring new technologies, products, and models, helping to improve agricultural productivity, reduce environmental pollution, and achieve green growth and sustainable development in rural areas.
4. Natural Disasters: Natural disasters have a direct impact on the rural economy and life. Areas frequently affected by disasters require more resources for post-disaster

reconstruction and risk prevention, which may limit investments in rural construction. However, strengthening disaster prevention and mitigation capabilities and ecological restoration can contribute to the long-term goals of green development in rural areas.

5. Fiscal Support for Agriculture: Fiscal expenditure on agriculture, forestry, and water affairs reflects the government's support for agricultural and rural development. This support can directly influence rural production conditions and quality of life through subsidies, infrastructure construction, and technology promotion, fostering the coordinated development of rural construction and green growth.
6. Scale of Operation: The ratio of grain-sown area to total crop-sown area reflects the level of specialization and scale of agricultural operations. Large-scale operations can improve agricultural productivity and resource utilization, promoting modern agricultural development and green growth in rural areas.
7. Education Investment: The proportion of education expenditure to total fiscal expenditure reflects the government's emphasis on education. Increased education investment can enhance the quality of the rural population and workforce skills, providing intellectual support and talent reserves for rural construction, and promoting inclusive green growth.
8. Environmental Investment: The proportion of environmental protection expenditure to total fiscal expenditure reflects the government's emphasis on environmental protection. Increasing environmental investment helps improve the rural ecological environment, reduce pollution and resource waste, and promote green development and sustainable construction in rural areas.

**Table 5.** Regression results of the bidirectional fixed-effects model.

| Variant | National Region | Eastern Region | Central Region | Western Region |
|---|---|---|---|---|
| Urbanization rate | 0.2124 ** (2.50) | 0.1047 (0.85) | 0.0115 *** (3.30) | 0.9988 *** (4.39) |
| Industrial structure | 0.5114 (0.68) | −0.0126 (−1.29) | 0.0185 (1.00) | 0.0301 * (1.80) |
| Innovation level | 0.0023 ** (2.55) | 0.0029 ** (2.40) | 0.0025 (1.51) | 0.0034 (1.38) |
| Natural disasters | −0.0014 *** (−2.87) | −0.0017 ** (−2.50) | −0.0021 ** (−2.12) | −0.0020 (−1.47) |
| Financial support for agriculture | 0.0075 *** (5.33) | 0.0041 * (1.79) | 0.0084 ** (2.20) | 0.0064 *** (3.14) |
| Large-scale business operation | 0.2874 ** (2.23) | 0.7376 *** (3.71) | 0.2699 (1.04) | −0.0549 (−0.26) |
| Investment in education | −0.1371 ** (−2.44) | 0.1893 * (1.70) | −0.2329 * (−1.97) | −0.2776 *** (−3.67) |
| Environmental inputs | −0.1696 (−0.53) | −0.0129 (−0.32) | 0.1697 * (1.68) | −0.1453 (−1.60) |
| Year FE | YES | YES | YES | YES |
| Province FE | YES | YES | YES | YES |
| Observed value | 360 | 156 | 72 | 132 |
| R-squared | 0.9983 | 0.9703 | 0.9820 | 0.9636 |

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively, with t-values in parentheses.

The test results show that the coefficient of the urban population ratio is positive, indicating that an increase in the urban population ratio can contribute to the improvement of the coupling and coordination of digital rural development and inclusive green growth at the national level and across all regions. However, the coefficients are significant only at the

national level and in the central and western regions. The industrial structure positively promotes the coupled and coordinated development at the national level and in the central and western regions, but only the coefficient for the western region is significant. Conversely, in the eastern region, industrial restructuring inhibits the coupling and coordination of the two aspects. The western region, rich in natural resources such as minerals and water, can better utilize these advantages to promote digital rural development and inclusive green growth through industrial restructuring, resulting in a significant coupled coordinated development effect. The eastern region, on the other hand, is relatively resource-poor and may face constraints in achieving similar effects through industrial restructuring.

The level of innovation significantly promotes the coupled and coordinated development of digital rural development and inclusive green growth at the national level and across regions but not in the central and western regions, where the lack of infrastructure and resources may limit the impact of innovation. Effective innovation requires robust research institutions, talent pools, and technical support, which are more prevalent in the eastern region than in the central and western regions, thus limiting the level and effectiveness of innovation there.

Natural disasters significantly inhibit the increase in coupled coordination at the national level and in the eastern and central regions, but the effect is not significant in the western region. This may be due to the higher frequency of natural disasters in the eastern and central regions compared to the western region, where such events are less common, resulting in a negligible impact on the degree of coupling and coordination.

Financial support for agriculture significantly contributes to the coupling and coordination degree across the entire country and in each region, indicating that fiscal support can enhance coupling coordination to a considerable extent. Scale operation significantly promotes this coupling and coordination at the national level and in the eastern region, but the effect is less pronounced in the central and western regions. In the eastern region, where land resources are relatively dispersed, scale operations can integrate land resources and improve farming efficiency and output. However, in the central and western regions, where land resources are more concentrated but farming conditions (e.g., soil quality, water availability) are poorer, the benefits of large-scale operations are limited, making it difficult to significantly enhance the degree of coupling and coordination.

Educational inputs significantly contribute to the coupling and coordination in the eastern region but inhibit improvement at the national level and in the central and western regions. The eastern region, with its strong educational infrastructure and resources, can more effectively transform educational inputs into human capital, directly promoting economic development and social progress, thereby improving the degree of coupling and coordination. In contrast, the central and western regions, with relatively weaker educational foundations, may find it challenging to quickly convert new educational inputs into effective human capital, requiring a longer time to see improvements in educational quality and level.

Environmental inputs significantly contribute to the coupling and coordination in the central region but inhibit it at the national level and in the eastern and western regions. The central region may have clearer policy orientation and stronger implementation in environmental governance, ensuring that environmental protection expenditures are effectively utilized and achieve significant results, thus enhancing the degree of coupling and coordination. Conversely, in the national, eastern, and western regions, discrepancies between policy implementation effectiveness and the actual outcomes of environmental expenditures may lead to a high proportion of these expenditures failing to significantly improve coupling and coordination.

## 5. Conclusions and Recommendations

### *5.1. Conclusions*

In this research, we utilized panel data from 30 Chinese provinces from 2011 to 2021 to systematically measure the development of digital villages and rural inclusive green growth.

By employing a relational coordination model, we assessed the coordinated development levels between these two aspects. The findings are as follows:

(1) Digital villages and inclusive green development in rural regions exhibit a consistent upward trajectory throughout China. The eastern region was at the forefront of the Digital Countryside Index's growth from 2011 to 2021, while the central region lagged behind. After 2014, the Rural Inclusive Green Development Index has continued to increase annually, with the eastern region outperforming the central region in terms of economic development and social inclusion. Collectively, the analyses demonstrate the increasing development of digital communities and inclusive green growth in rural areas.

(2) With regard to the time-series evolution, the rural inclusive green growth and China's digital countryside coupling coordination degree was minimal between 2011 and 2020 and peaked in 2021. The advancement of the digital countryside fell behind that of rural inclusive green growth (type a) from 2011 to 2016, and digital villages expanded in tandem with rural inclusive green growth (type c) between 2016 and 2021. The modified model's coupling coordination level results indicate that the values of the coupling coordination levels for the two indices have decreased, but this has not altered the trend of development for the coupling coordination levels in cities and provinces; this result is essentially consistent with previous empirical findings.

(3) With regard to spatial variations, the coupling coordination degree trends are essentially identical across all regions: they increase annually. Nevertheless, the coupling coordination degree is the lowest in the western region and the highest in the central region, followed by the eastern region. Furthermore, while both the western and central regions are situated above the average coordination level in China, this level is still considerably different from the average level in the eastern region. The eastern region's coupling coordination degree successfully completed the transition from rural inclusive green growth (type a), surpassing digital rural development to their synergistic development (type c) in 2014. Similarly, the central region accomplished this transition in 2021, whereas the western region had yet to do so as of 2021. Furthermore, following the correction, we observed a significant spatial evolution effect. From the results of Kernel density estimation, China's digital countryside and rural inclusive green growth coupling coordination shows an upward trend, with obvious stage characteristics.

(4) The increase in urbanization rate, the advancement in innovation levels, the reduction in natural disasters, the increase in financial support for agriculture, and the improvement in the capability of large-scale operations all contribute positively to the coupling and coordination of digital village construction and inclusive green growth in rural areas. These factors are crucial drivers in enhancing the synergy and alignment between digital rural development and sustainable, inclusive growth.

### *5.2. Recommendations*

To enhance the synergistic growth of China's digital countryside and rural inclusive green development, the following policy recommendations are proposed: (1) the enhancement of digital infrastructure and green technology in the western region should be prioritized to reduce the disparities with the eastern and central regions; (2) region-specific policies that align with the local conditions should be implemented, such as advancing the integration of economic growth with environmental sustainability in the eastern region and reinforcing social inclusion initiatives in the central region; (3) the successful coordination model from the eastern region should be adapted to foster similar development across other regions; (4) mechanisms for coordinated action at both the local and national levels should be developed and refined to ensure cohesive strategy implementation; and (5) a comprehensive monitoring system should be set up to regularly evaluate the effectiveness of policies and their developmental impacts, adjusting the strategies as necessary to

meet regional demands. These measures aim to drive more equitable and harmonized advancement in digital and green rural areas across China.

**Author Contributions:** Conceptualization, L.C. and Y.W.; methodology, L.C.; software, Y.Y.; validation, L.C., Y.W. and Y.Y.; formal analysis, L.C.; investigation, Y.W.; resources, L.C.; data curation, Y.W.; writing—original draft preparation, L.C.; writing—review and editing, Y.Y. and B.X.; visualization, Y.W. and Z.Z.; supervision, L.C. and X.Y. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was funded by the National Social Science Foundation (19BGL087) of China.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest:** The authors declare that they have no conflicts of interest.

## Appendix A

**Table A1.** Coupled harmonization of digital villages and inclusive green growth in villages at the provincial level in China, 2011–2022. Note: a for digital villages lagging behind rural inclusive green growth, b for digital villages leading rural inclusive green growth, c for digital villages synergizing with rural inclusive green growth.

| Region | Province | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| eastern part | Beijing | 0.358 a | 0.386 a | 0.40 a | 0.412 a | 0.423 a | 0.441 a | 0.462 a | 0.465 a | 0.481 a | 0.492 a | 0.515 c | 0.542 c |
| | Tianjin | 0.287 a | 0.306 c | 0.327 c | 0.333 c | 0.348 c | 0.361 c | 0.37 c | 0.364 a | 0.373 a | 0.398 a | 0.416 a | 0.441 a |
| | Hebei | 0.417 a | 0.432 a | 0.445 a | 0.455 a | 0.466 a | 0.483 c | 0.499 c | 0.512 c | 0.527 c | 0.55 c | 0.564 c | 0.598 c |
| | Shanghai | 0.327 a | 0.345 a | 0.365 a | 0.395 a | 0.397 a | 0.411 a | 0.422 a | 0.442 a | 0.459 a | 0.476 a | 0.515 a | 0.57 a |
| | Jiangsu | 0.436 c | 0.459 c | 0.471 c | 0.478 c | 0.5 c | 0.515 c | 0.541 c | 0.559 c | 0.584 c | 0.59 c | 0.611 c | 0.66 b |
| | Zhejiang | 0.422 c | 0.441 c | 0.461 c | 0.472 c | 0.484 c | 0.512 c | 0.553 c | 0.582 b | 0.61 b | 0.631 b | 0.671 b | 0.713 b |
| | Fujian | 0.351 c | 0.369 c | 0.383 c | 0.39 c | 0.407 c | 0.421 c | 0.447 c | 0.465 c | 0.482 c | 0.494 c | 0.52 c | 0.556 c |
| | Shandong | 0.461 a | 0.484 a | 0.502 a | 0.5 c | 0.533 a | 0.546 c | 0.568 c | 0.582 c | 0.589 c | 0.613 c | 0.635 c | 0.678 b |
| | Guangdong | 0.446 a | 0.465 a | 0.478 c | 0.488 c | 0.508 c | 0.531 c | 0.559 c | 0.582 c | 0.608 b | 0.635 b | 0.659 b | 0.699 b |
| | Hainan | 0.222 a | 0.245 a | 0.264 a | 0.278 a | 0.294 a | 0.3 a | 0.312 a | 0.32 a | 0.328 a | 0.336 a | 0.351 a | 0.376 a |
| | Heilongjiang | 0.352 a | 0.371 a | 0.384 c | 0.391 c | 0.396 c | 0.393 c | 0.397 c | 0.404 c | 0.404 c | 0.414 a | 0.426 a | 0.459 c |
| | Jilin | 0.315 c | 0.33 c | 0.339 c | 0.348 c | 0.364 c | 0.368 c | 0.374 c | 0.38 c | 0.379 c | 0.391 c | 0.396 c | 0.419 c |
| | Liaolin | 0.355 a | 0.37 c | 0.383 c | 0.384 c | 0.402 c | 0.409 c | 0.423 c | 0.419 a | 0.428 a | 0.442 a | 0.446 a | 0.462 c |
| | Average | 0.365 a | 0.385 a | 0.400 c | 0.410 c | 0.425 c | 0.438 c | 0.456 c | 0.467 c | 0.481 c | 0.497 c | 0.517 c | 0.552 c |
| central part | Shanxi | 0.325 c | 0.338 c | 0.353 c | 0.361 c | 0.373 c | 0.379 c | 0.368 c | 0.369 c | 0.378 c | 0.389 c | 0.412 c | 0.447 c |
| | Jiangxi | 0.33 a | 0.348 a | 0.357 a | 0.368 a | 0.382 a | 0.397 a | 0.414 a | 0.429 a | 0.437 a | 0.454 a | 0.464 a | 0.498 a |
| | Henan | 0.421 a | 0.436 a | 0.454 a | 0.463 a | 0.473 a | 0.483 c | 0.513 a | 0.529 c | 0.543 a | 0.568 a | 0.586 a | 0.631 c |
| | Hubei | 0.381 a | 0.4 c | 0.414 c | 0.418 c | 0.434 c | 0.444 c | 0.462 c | 0.473 c | 0.488 c | 0.499 c | 0.518 c | 0.555 c |
| | Hunan | 0.382 a | 0.401 a | 0.415 a | 0.415 a | 0.435 a | 0.449 a | 0.466 a | 0.482 c | 0.502 c | 0.516 a | 0.529 c | 0.555 c |
| | Anhui | 0.339 a | 0.36 a | 0.379 a | 0.376 c | 0.398 c | 0.409 c | 0.424 c | 0.455 c | 0.466 c | 0.491 a | 0.508 c | 0.542 c |
| | Average | 0.363 a | 0.381 a | 0.395 a | 0.400 a | 0.416 c | 0.427 c | 0.441 c | 0.456 c | 0.469 c | 0.486 c | 0.503 c | 0.538 c |

**Table A1.** *Cont.*

| Region | Province | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| western part | Neimenggu | 0.325 a | 0.344 c | 0.361 c | 0.371 c | 0.379 c | 0.388 c | 0.401 c | 0.402 a | 0.409 a | 0.42 a | 0.428 a | 0.45 a |
| | Guangxi | 0.33 a | 0.346 a | 0.36 c | 0.358 c | 0.375 c | 0.386 c | 0.411 c | 0.422 c | 0.434 c | 0.453 c | 0.468 c | 0.501 c |
| | Chongqing | 0.295 a | 0.315 a | 0.322 a | 0.331 c | 0.344 c | 0.359 c | 0.376 c | 0.388 c | 0.401 c | 0.42 c | 0.435 c | 0.471 c |
| | Sichuan | 0.425 a | 0.444 a | 0.457 a | 0.47 a | 0.483 a | 0.506 a | 0.529 a | 0.553 a | 0.571 a | 0.591 c | 0.599 c | 0.634 c |
| | Guizhou | 0.269 a | 0.288 a | 0.307 a | 0.322 a | 0.348 a | 0.366 a | 0.391 c | 0.423 c | 0.429 c | 0.445 c | 0.46 c | 0.483 c |
| | Yunnan | 0.315 a | 0.332 a | 0.354 a | 0.365 c | 0.383 c | 0.397 c | 0.424 c | 0.441 c | 0.462 c | 0.479 c | 0.497 c | 0.529 c |
| | Shanxi | 0.34 a | 0.351 a | 0.364 a | 0.373 c | 0.385 c | 0.397 c | 0.41 c | 0.43 c | 0.437 c | 0.45 c | 0.461 c | 0.489 c |
| | Gansu | 0.281 a | 0.3 c | 0.314 c | 0.324 c | 0.343 c | 0.351 c | 0.357 c | 0.365 c | 0.372 c | 0.384 c | 0.396 c | 0.419 c |
| | Qinghai | 0.201 c | 0.221 c | 0.24 c | 0.256 c | 0.27 c | 0.285 c | 0.297 c | 0.304 c | 0.31 c | 0.324 c | 0.337 c | 0.346 c |
| | Ningxia | 0.203 c | 0.227 c | 0.247 c | 0.261 c | 0.278 c | 0.289 c | 0.3 c | 0.31 c | 0.309 c | 0.323 c | 0.334 c | 0.341 c |
| | Xinjiang | 0.275 c | 0.293 c | 0.305 c | 0.313 c | 0.326 c | 0.337 c | 0.352 c | 0.36 c | 0.36 c | 0.376 c | 0.396 c | 0.426 c |
| | Average | 0.296 a | 0.315 a | 0.330 a | 0.340 c | 0.356 c | 0.369 c | 0.386 c | 0.400 c | 0.409 c | 0.424 c | 0.437 c | 0.463 c |
| national average | | 0.340 a | 0.358 a | 0.374 a | 0.382 c | 0.398 c | 0.410 c | 0.427 c | 0.440 c | 0.452 c | 0.468 c | 0.485 c | 0.516 c |

## Appendix B

**Table A2.** Degree of coupling harmonization between digital villages and rural inclusive green growth based on the modified coupling model. Note: a for digital villages lagging behind rural inclusive green growth, b for digital villages leading rural inclusive green growth, c for digital villages synergizing with rural inclusive green growth.

| Region | Province | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| eastern part | Beijing | 0.293 a | 0.316 a | 0.338 a | 0.35 a | 0.362 a | 0.372 a | 0.401 a | 0.404 a | 0.424 a | 0.436 a | 0.467 c | 0.508 c |
| | Tianjin | 0.222 a | 0.248 c | 0.267 c | 0.276 c | 0.289 c | 0.305 c | 0.312 c | 0.304 a | 0.31 a | 0.328 a | 0.342 a | 0.371 a |
| | Hebei | 0.328 a | 0.345 a | 0.371 a | 0.392 a | 0.409 a | 0.429 c | 0.453 c | 0.473 c | 0.5 c | 0.529 c | 0.552 c | 0.578 c |
| | Shanghai | 0.257 a | 0.273 a | 0.295 a | 0.326 a | 0.332 a | 0.349 a | 0.356 a | 0.361 a | 0.374 a | 0.389 a | 0.421 a | 0.473 a |
| | Jiangsu | 0.404 c | 0.437 c | 0.452 c | 0.469 c | 0.499 c | 0.509 c | 0.539 c | 0.545 c | 0.556 c | 0.554 c | 0.578 c | 0.59 b |
| | Zhejiang | 0.369 c | 0.39 c | 0.41 c | 0.424 c | 0.447 c | 0.494 c | 0.533 c | 0.528 b | 0.522 b | 0.536 b | 0.553 b | 0.561 b |
| | Fujian | 0.306 c | 0.329 c | 0.341 c | 0.36 c | 0.384 c | 0.406 c | 0.435 c | 0.461 c | 0.477 c | 0.491 c | 0.507 c | 0.521 c |
| | Shandong | 0.388 a | 0.417 a | 0.438 a | 0.447 c | 0.477 a | 0.509 c | 0.554 c | 0.578 c | 0.585 c | 0.598 c | 0.601 c | 0.595 b |
| | Guangdong | 0.384 a | 0.407 a | 0.432 c | 0.447 c | 0.478 c | 0.515 c | 0.545 c | 0.544 c | 0.545 b | 0.559 b | 0.563 b | 0.548 b |
| | Hainan | 0.165 a | 0.186 a | 0.204 a | 0.216 a | 0.232 a | 0.236 a | 0.248 a | 0.256 a | 0.262 a | 0.266 a | 0.279 a | 0.301 a |
| | Heilongjiang | 0.286 a | 0.31 a | 0.328 c | 0.342 c | 0.344 c | 0.34 c | 0.346 c | 0.348 c | 0.347 c | 0.354 a | 0.367 a | 0.416 c |
| | Jilin | 0.26 c | 0.279 c | 0.292 c | 0.305 c | 0.322 c | 0.33 c | 0.337 c | 0.337 c | 0.33 c | 0.337 c | 0.341 c | 0.373 c |
| | Liaolin | 0.294 a | 0.312 c | 0.328 c | 0.328 c | 0.349 c | 0.359 c | 0.37 c | 0.359 a | 0.367 a | 0.373 a | 0.378 a | 0.413 c |
| | Average | 0.304 a | 0.327 a | 0.346 c | 0.360 c | 0.379 c | 0.396 c | 0.418 c | 0.423 c | 0.431 c | 0.442 c | 0.458 c | 0.481 c |
| central part | Shanxi | 0.268 c | 0.287 c | 0.304 c | 0.313 c | 0.331 c | 0.345 c | 0.319 c | 0.318 c | 0.324 c | 0.333 c | 0.36 c | 0.415 c |
| | Jiangxi | 0.251 a | 0.27 a | 0.282 a | 0.295 a | 0.313 a | 0.329 a | 0.344 a | 0.361 a | 0.367 a | 0.381 a | 0.391 a | 0.44 a |
| | Henan | 0.33 a | 0.349 a | 0.371 a | 0.39 a | 0.417 a | 0.437 c | 0.457 a | 0.478 c | 0.484 a | 0.512 a | 0.531 a | 0.607 c |
| | Hubei | 0.314 a | 0.342 c | 0.358 c | 0.369 c | 0.388 c | 0.405 c | 0.416 c | 0.434 c | 0.457 c | 0.46 c | 0.49 c | 0.555 c |
| | Hunan | 0.297 a | 0.318 a | 0.333 a | 0.346 a | 0.367 a | 0.386 a | 0.404 a | 0.43 c | 0.45 c | 0.459 a | 0.477 c | 0.525 c |
| | Anhui | 0.266 a | 0.292 a | 0.315 a | 0.334 c | 0.358 c | 0.37 c | 0.382 c | 0.406 c | 0.414 c | 0.434 a | 0.46 c | 0.525 c |
| | Average | 0.288 a | 0.310 a | 0.327 a | 0.341 a | 0.362 c | 0.379 c | 0.387 c | 0.404 c | 0.416 c | 0.430 c | 0.452 c | 0.511 c |

**Table A2.** *Cont.*

| Region | Province | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| western part | Neimenggu | 0.265 a | 0.286 c | 0.306 c | 0.321 c | 0.331 c | 0.342 c | 0.35 c | 0.341 a | 0.347 a | 0.354 a | 0.36 a | 0.387 a |
| | Guangxi | 0.264 a | 0.284 a | 0.302 c | 0.308 c | 0.332 c | 0.347 c | 0.364 c | 0.384 c | 0.396 c | 0.412 c | 0.445 c | 0.5 c |
| | Chongqing | 0.227 a | 0.246 a | 0.258 a | 0.274 c | 0.288 c | 0.302 c | 0.32 c | 0.332 c | 0.344 c | 0.364 c | 0.382 c | 0.442 c |
| | Sichuan | 0.328 a | 0.349 a | 0.362 a | 0.381 a | 0.403 a | 0.426 a | 0.451 a | 0.489 a | 0.515 a | 0.544 c | 0.557 c | 0.633 c |
| | Guizhou | 0.203 a | 0.222 a | 0.238 a | 0.258 a | 0.283 a | 0.304 a | 0.336 c | 0.373 c | 0.378 c | 0.397 c | 0.418 c | 0.459 c |
| | Yunnan | 0.253 a | 0.272 a | 0.291 a | 0.307 c | 0.331 c | 0.345 c | 0.372 c | 0.395 c | 0.42 c | 0.443 c | 0.467 c | 0.521 c |
| | Shanxi | 0.273 a | 0.287 a | 0.303 a | 0.316 c | 0.336 c | 0.352 c | 0.371 c | 0.389 c | 0.398 c | 0.409 c | 0.42 c | 0.468 c |
| | Gansu | 0.22 a | 0.241 c | 0.258 c | 0.274 c | 0.295 c | 0.309 c | 0.306 c | 0.315 c | 0.326 c | 0.335 c | 0.345 c | 0.372 c |
| | Qinghai | 0.158 c | 0.18 c | 0.199 c | 0.216 c | 0.234 c | 0.248 c | 0.256 c | 0.261 c | 0.264 c | 0.272 c | 0.281 c | 0.287 c |
| | Ningxia | 0.159 c | 0.182 c | 0.201 c | 0.213 c | 0.23 c | 0.239 c | 0.251 c | 0.262 c | 0.259 c | 0.268 c | 0.279 c | 0.285 c |
| | Xinjiang | 0.228 c | 0.25 c | 0.261 c | 0.272 c | 0.291 c | 0.299 c | 0.322 c | 0.323 c | 0.315 c | 0.331 c | 0.354 c | 0.387 c |
| | Average | 0.234 a | 0.255 a | 0.271 a | 0.286 c | 0.305 c | 0.320 c | 0.336 c | 0.351 c | 0.360 c | 0.375 c | 0.392 c | 0.431 c |
| national average | | 0.275 a | 0.297 a | 0.315 a | 0.329 c | 0.348 c | 0.365 c | 0.382 c | 0.393 c | 0.402 c | 0.415 c | 0.432 c | 0.469 c |

## References


1. Rammelt, C.F.; Gupta, J. Inclusive is not an adjective, it transforms development: A post-growth interpretation of Inclusive Development. *Environ. Sci. Policy* **2021**, *124*, 144–155. [CrossRef]
2. Zhou, X.L.; Wu, W.L. Measurement and analysis of inclusive green growth in China. *J. Quant. Technol. Econ.* **2018**, *35*, 3–20.
3. Zheng, C.D. Research on Poverty Reduction Policy in Concentrated Contiguous Special Difficulties Ethnic Areas Based on the Perspective of Inclusive Green Development. *J. South-Cent. Minzu Univ. Humanit. Soc. Sci.* **2016**, *36*, 115–121.
4. Xu, W.; Xu, F.; Liu, Y.; Zhang, D. Assessment of rural ecological environment development in China's moderately developed areas: A case study of Xinxiang, Henan province. *Environ. Monit. Assess.* **2021**, *193*, 1–25. [CrossRef] [PubMed]
5. Boraita, R.J.; Alsina, D.A.; Ibort, E.G.; Torres, J.M.D. Quality of life related to health and habits: Differences between adolescents in rural and urban environments. *An. Pediatría* **2022**, *96*, 196–202. [CrossRef]
6. Wei, M.S.; Yan, T.W.; Ros, H. Impacts of scale operation and technological progress on the green and low-carbon development of agriculture—A quasi-natural experiment based on the establishment of a major grain producing area. *Chin. Rural Econ.* **2023**, *2*, 41–65.
7. Sturgeon, T.J. Upgrading strategies for the digital economy. *Glob. Strategy J.* **2021**, *11*, 34–57. [CrossRef]
8. Pan, W.; Xie, T.; Wang, Z.; Ma, L. Digital economy: An innovation driver for total factor productivity. *J. Bus. Res.* **2022**, *139*, 303–311. [CrossRef]
9. Hao, A.M.; Tan, J.Y. The impact of digital village construction on the resilience of China's food system. *J. South China Agric. Univ. Soc. Sci. Ed.* **2022**, *21*, 10–24.
10. Li, B.Q.; Zhou, Q.X.; Yue, H.Z. An empirical test of the impact of digital village construction on industrial prosperity. *Stat. Decis.* **2022**, *38*, 5–10.
11. Zhao, J.J.; Wei, J.; Liu, T.J. Research on the impact and mechanism of digital village development on farmers' entrepreneurship. *China Rural Econ.* **2023**, *5*, 61–80.
12. Shen, F.W.; Ye, W.X. Digital village construction: A strategic choice for achieving high-quality rural revitalisation. *J. Nanjing Agric. Univ. Soc. Sci. Ed.* **2021**, *21*, 41–53.
13. Zhao, J.J.; Sun, X.L.; Su, L.L. The impact of digital village development on rural residents' household consumption—Based on matched data from county digital village index and China household tracking survey. *J. China Agric. Univ. Soc. Sci.* **2022**, *39*, 114–132.
14. Su, L.L.; Peng, Y.L. Digital education, digital literacy and farmers' digital life. *J. South China Agric. Univ. Soc. Sci. Ed.* **2021**, *20*, 27–40.
15. Han, R.B. Agile governance-driven rural digital governance. *J. South China Agric. Univ. Soc. Sci. Ed.* **2021**, *20*, 132–140.
16. Zha, R.B.; Zhong, C.B. Digital Rural Construction and County Ecological Environment Quality—Empirical Evidence from Comprehensive Demonstration Policies of E-commerce into Rural Areas. *Contemp. Econ. Manag.* **2023**, *45*, 54–65.
17. Du, J.J.; Zhang, Y.D.; Liu, B.M.; Dong, R.H. Impact of digital countryside on green total factor productivity in agriculture and its mechanism of action. *China Popul. Resour. Environ.* **2023**, *33*, 165–175.
18. Wang, X.S.; Xie, S.X. How have international agricultural commodity prices affected Chinese agricultural commodity prices? *Econ. Res. J.* **2012**, *47*, 141–153.
19. Xiong, X.; Nie, F.Y.; Zhu, H.B. How to effectively dock agricultural products e-commerce market for small farmers in western poverty-stricken areas—A case study of Xiushan County, Chongqing based on the perspective of limited capacity. *China Rural Econ.* **2023**, *4*, 68–89.

20. Fang, K.; Li, F.; Jin, M. Research on digital village public service system based on holistic governance. *E-Government* **2019**, *11*, 72–81.
21. Ma, W.; Zhang, R.Z. Research on the impact effect of the breadth and depth of digital finance on narrowing the development gap between urban and rural areas—Based on the synergistic effect perspective of residents' education. *J. Agrotech. Econ.* **2022**, *2*, 62–76.
22. Xie, K.; Yi, F.M.; Gu, F.T. Big data-driven digital transformation and innovation in agriculture. *Issues Agric. Econ.* **2022**, *5*, 37–48.
23. Wen, T.; Chen, Y.M. Integration and development of digital economy and agricultural and rural economy: Practice mode, realistic obstacles and breakthrough path. *Issues Agric. Econ.* **2020**, *7*, 118–129.
24. Zhang, Y.; Feng, M.W.; Yi, F.J. Research on the effect and mechanism of rural digital governance on farmers' waste classification. *World Agric.* **2023**, *11*, 78–90.
25. Bai, F.C.; Gao, P.; Zheng, W.L. Ecological resources empowering rural commons—The facilitating role of digital economy. *J. China Agric. Univ.* **2023**, *28*, 263–275.
26. Wen, Y.; Jiang, C. Attention Redistribution, External Resource Dependence and Digital Village Governance Performance—A Group Analysis Based on the TOE Framework. *Chin. Public Adm.* **2023**, *7*, 58–67.
27. Zhao, W.; Huang, L.; Li, W.; Peng, W.H. Divergence in the level of inclusive green development and its drivers in rural China. *Econ. Geogr.* **2023**, *43*, 68–77.
28. Zeng, Y.W.; Song, Y.X.; Lin, X.Z.; Fu, X.L. Ruminations on some issues of digital village construction in China. *China Rural Econ.* **2021**, *4*, 21–35.
29. Zhang, T.; Li, J.C. Network infrastructure, inclusive green growth and regional disparities—Causal inference based on dual machine learning. *J. Quant. Technol. Econ.* **2023**, *40*, 113–135.
30. Zhu, H.G.; Chen, H. Level measurement, spatial and temporal evolution and promotion path of digital village development in China. *Issues Agric. Econ.* **2023**, *3*, 21–33.
31. Lin, Y.M.; Cheng, Q.W.; Xu, A.X. Research on the Impact of Digital Village Construction on Urban-Rural Integrated Development-Empirical Evidence Based on Provincial Panel Data from 2012–2020. *J. Fujian Prov. Comm. Party Sch. CPC Fujian Acad. Gov.* **2023**, *4*, 101–111.
32. Yin, H.D.; Huo, P.; Wang, S.G. Digital transformation of agriculture and rural areas: Reality representation, influence mechanism and promotion strategy. *Reform* **2020**, *12*, 48–56.
33. Wang, F.; Sun, S.H.; Liu, T.J. Has the development of digital economy advanced the change of agricultural production methods-Evidence from prefecture-level cities in the Yellow River Basin. *China Rural Econ.* **2023**, *9*, 122–143.
34. Ji, Z.H. Spatial differences and driving mechanisms of high-quality agricultural and rural development in China. *J. Quant. Technol. Econ.* **2021**, *38*, 25–44.
35. Liu, Z.Y.; Zhe, V. Regional differences and distributional dynamics evolution of high-quality agricultural development in China. *J. Quant. Technol. Econ.* **2021**, *38*, 28–44.
36. Zhang, J.X.; Hou, Y.Z.; Liu, P.L.; He, J.W.; Zhuo, X. Target requirements and strategic path of high-quality development. *J. Manag. World* **2019**, *35*, 1–7.
37. Xu, X.; Wang, Y.Y. Measurement of China's rural revitalisation level, decomposition of regional differences and dynamic evolution. *J. Quant. Technol. Econ.* **2022**, *39*, 64–83.
38. Jia, J.; Li, X.F.; Shen, Y. Indicator system construction and empirical analysis of rural revitalisation strategy. *Financ. Econ.* **2018**, *11*, 70–82.
39. Yan, Z.F.; Wu, F.W. From binary division to integrated development—Research on evaluation index system of rural revitalisation. *Economist* **2019**, *6*, 90–103.
40. Pi, J.C.; Song, D.Q. Measurement and judgement of the coordinated development of China's manufacturing and real estate industries. *J. Financ. Res.* **2021**, *9*, 72–90.
41. Liu, T.; Xu, Z.Y.; Zhang, K.L. The impact of digital finance on the synergy between economic development and ecological environment. *Mod. Financ. Econ.—J. Tianjin Univ. Financ. Econ.* **2022**, *42*, 1–36.
42. Liu, C.Y.; Liu, Y.Y.; Ding, R.G. Coupling analysis of new urbanisation and ecological environment in Fujian Province. *Chin. J. Appl. Ecol.* **2018**, *1*, 1–14.
43. Tan, J.T.; Zhang, P.Y.; Li, J.; Liu, S.W. Spatio-temporal evolution characteristics of coordinated development of urbanisation and ecological environment in Jilin Province. *Chin. J. Appl. Ecol.* **2015**, *26*, 3827–3834.
44. Wang, S.J.; Kong, W.; Ren, L.; Zi, D.D.; Dai, B.T. Misconceptions and corrections of the domestic coupled coordination degree model. *J. Nat. Resour.* **2021**, *36*, 793–810.


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

land

MDPI

*Article*

# Exploring the Long-Term Changes in Visual Attributes of Urban Green Spaces Using Point Clouds

**Xiaohan Zhang [1], Yuhao Fang [2], Guanting Zhang [3] and Shi Cheng [2,4,*]**

[1] Department of Architecture, Technical University of Munich, 80333 Munich, Germany; xiao-han.zhang@tum.de
[2] Department of Architecture, Southeast University, Nanjing 210096, China; fangyuhao@seu.edu.cn
[3] College of Architecture, Nanjing Tech University, Nanjing 211816, China; guanting_zhang@163.com
[4] Chinese National Visual Image Research Base, Southeast University, Nanjing 210096, China
* Correspondence: 101300063@seu.edu.cn

**Abstract:** The visual attributes of urban green spaces influence people's perceptions, preferences, and behavioural activities. While many studies have established correlations between landscape perception and visual attributes, they often focus on specific timeframes and overlook dynamic changes in the spatial form of urban green spaces. This study aims to explore the long-term changes in the visual attributes of urban green spaces. We propose a method to quantitatively analyse changes in visual attributes using point clouds to simulate visual interfaces. Using an unmanned aerial vehicle, we conducted a five-axis tilt photography survey of Qinglvyuan Park in Nanjing, China, in August 2018 and September 2023. Point cloud models were generated for the two periods, and five visual attribute indicators, openness (OP), depth variance (DV), green view ratio (GVR), sky view ratio (SVR), and skyline complexity (SC), were analysed for long-term changes. The results indicate that OP, DV, and SVR decreased after five years, while GVR increased. The maximum increase in GVR was 26.6%, and the maximum decrease in OP was 12.8%. There is a positive correlation between GVR and its change (d_GVR). Conversely, there are negative correlations between SC and its change (d_SC), as well as between SVR and d_GVR. Tree growth emerged as a primary factor influencing changes in the visual attributes of urban green spaces. This study highlights the importance of adopting a long-term and dynamic perspective in visual landscape studies, as well as in landscape design and maintenance practices. Future research on predicting long-term changes in the visual attributes of urban green spaces should focus on understanding the relationships between tree properties and environmental conditions.

**Keywords:** urban green spaces; visual attributes; long-term changes; point clouds; dynamic design and maintenance

**Citation:** Zhang, X.; Fang, Y.; Zhang, G.; Cheng, S. Exploring the Long-Term Changes in Visual Attributes of Urban Green Spaces Using Point Clouds. *Land* **2024**, *13*, 884. https://doi.org/10.3390/land13060884

Academic Editors: Fabrizio Battisti and Maria Rosa Trovato

Received: 30 April 2024
Revised: 29 May 2024
Accepted: 14 June 2024
Published: 18 June 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

With rapid urbanisation, city residents are increasingly susceptible to various mental and physical ailments, such as anxiety, depression, and obesity [1–3]. Urban green space serves as a crucial urban green infrastructure capable of alleviating stress and restoring attention [4–6]. Evidence has shown that living in areas with more urban green spaces leads to lower stress levels and better mental health outcomes [7]. Furthermore, urban green space with good spatial quality can positively impact people's outdoor activities, which can also contribute to reducing the risk of chronic physical diseases [8]. Therefore, creating high-quality urban green spaces to promote people's health and well-being has become one of the critical concerns of urban designers.

The visual quality of urban green space is one of the key factors influencing landscape preferences and attracting human activities [9]. Previous studies have proposed various theories to understand the relationship between human perceptions and preferences in landscape environments. For example, Appleton proposed the Prospect–Refuge theory,

which suggests that in a landscape environment, people play the roles of "prey" and "hunter" at the same time and need to be in a space with a sense of shelter and safety while looking at the landscape from a distance [10]. Information processing theory, proposed by Kaplan and Kaplan, suggests that favoured landscapes require "Making sense" and "Involvement" [11]. Since then, with the development of the field of landscape visual quality assessment, the analysis framework and quantitative assessment indicator system for visual landscapes have been gradually built up. For instance, Grahn and Stigsdotter proposed the theory of PSD (perceived sensory dimensions), which includes eight perceptual dimensions, such as nature, scene, shelter, and space [12]. Tveit et al. developed a theoretical terminology for visual quality, including four levels (concepts, dimensions, landscape attributes, and indicators [13]. Naturalness is regarded as one of the critical factors of visual quality. Related indicators include water surface rate and green visibility [14–16]. Visual scale can describe the visibility and openness of landscape space, and indicators include sky view, openness, etc., [17,18].

The relationship between the various visual attributes of landscape spaces and landscape preference has been established. Zhang et al. explored the relationship between the four visual attribute indicators (openness, richness, order, and depth) and landscape preference by using a photographic questionnaire and found that the landscapes with high openness and order had a higher preference [19]. Similarly, studies have shown that landscapes with appropriate openness are preferred more, and they can promote residents' outdoor activities and communication [20]. Furthermore, Zhu et al. experimentally determined that scenes were most suitable for the human brain when the green view ratio reached 60–80% [21]. The visual attributes of landscape spaces have been found to play an essential role in predicting people's preferences for specific landscape spaces and potential behaviour [19]. Therefore, an in-depth study of the visual attributes of landscapes can not only help designers understand the spatial and visual characteristics of a site and assess the visual quality of landscapes but also help in landscape planning and design, management decisions, and related policymaking [22].

However, previous studies on the visual attributes and preferences of urban green space have tended to overlook the dynamic changes in landscape space. Landscape spaces at a particular time have often been used as the experimental material for landscape perception and preference studies. While monitoring the dynamic change in landscapes has long been an important issue in the field of urban environmental resource management and spatial planning, it tends to focus on the dynamic change in landscapes at large scales, such as cities or regions [23–25]. Although we have limited exploration of the long-term changes in the visual attributes of landscape spaces, dynamic changes in landscape space are objective. For example, Ode et al. proposed a measure of visual scale using a fusion data source in which two photographs of the same landscape space taken 20 years apart showed huge differences [26].

The dynamic growth of plants, the renewal and renovation of green spaces, and the pruning and death of trees are the objective causes of changes in the spatial form of the landscape. Changes in vegetation occur due to factors such as resident preferences and activity needs [27]. Factors such as tree species, age, and habitat conditions can also lead to variations in tree growth rate [28–30]. Pruning is a common maintenance practice for urban trees. Although trees could grow better without intervention, periodic pruning is necessary to maintain their desired appearance and to prevent safety hazards [31]. Similarly, the trees growing in urban environments need to be pruned regularly to improve views, reduce conflicts with buildings and infrastructure, and reduce wind resistance [32].

Maintaining urban green spaces in a static spatial form through extensive pruning and other high-intensity maintenance practices to meet people's visual preferences is both costly and detrimental to the ecological services provided by vegetation, including trees [31]. We should try to design and maintain urban green spaces in a green and sustainable way that considers landscape preferences [33]. Therefore, conducting a comprehensive investigation

into the changes in the visual attributes of urban green spaces over time is essential to inform design and long-term maintenance strategies.

Although there are currently methods available for the study of landscape change at a large scale, approaches to the study of long-term changes in the visual attributes of urban green spaces are still limited. For example, previous studies on landscape changes mainly focused on the use of remote sensing, historical maps, and GIS to analyse long-term changes in urban green space patterns or urban vegetation [34]. Recording the landscape environment by taking photos repeatedly at the same location can intuitively reflect the changing characteristics of the landscape and is closer to the actual perception of the human eye [23,35]. Despite its suitability for judging the changes in landscape elements by using two-dimensional image analysis, it lacks the ability to analyse three-dimensional spatial attributes. Due to the limitation of factors such as the photo angle, it is currently only used in the study of the natural environment. Walz et al. [36] proposed a method for analysing landscape structure considering time and three-dimensional features and proposed some three-dimensional landscape metrics, such as average surface roughness, edge contrast index, proximity, etc. However, the method is aimed at the analysis of landscape structure, which is difficult to apply to the study of the visual attributes of urban green spaces. Thus, we need to develop a method that can accurately record the spatial changes in urban green space, simulate the visual perception of the people, and analyse the visual attributes of the urban green space.

The development of digital technology presents an opportunity for the precise quantification of visual attributes and the accurate documentation of morphological changes in urban green spaces. Utilising two-dimensional images such as photographs, street view images, and panoramas allows for the convenient analysis of the elemental composition of the visual interface [22,37]. Yang et al. employed machine learning techniques to semantically segment images and then calculated indicators such as the green view ratio of landscape spaces [38]. Additionally, point cloud models can be processed to generate visual interfaces corresponding to viewpoints, facilitating the analysis of visual attribute indicators [39]. Point cloud models, capable of recording 3D shape information with high accuracy, offer invaluable support for documenting spatial form differences in green spaces over time and comparing visual features across different periods [40,41].

The aim of this study is to investigate whether visual attributes change dynamically in urban green spaces and to what extent. Based on this, we asked the following research questions:

1. How can we identify long-term changes in the visual attributes of urban green spaces?
2. What trends do the visual attributes of urban green spaces have?
3. What is the relationship between the change in the visual attributes of urban green spaces and their initial attributes?

This study attempted to explore the long-term changes in visual attributes by collecting the spatial data of the same urban green space at five-year intervals. We selected Qinglvyuan Park in Nanjing, China, as the study area and obtained point cloud models using unmanned aerial five-axis tilt photography in 2018 and 2023. After processing the point cloud model, we used a virtual camera to simulate the human visual interface in the green space and then quantitatively analysed the five visual attribute indicators. We compared the differences in indicator values before and after the five-year period and conducted correlation analyses between the changed values and the initial values of the indicators. This study not only explores the dynamic change characteristics of visual attributes within urban green spaces but also aims to provide support for their dynamic maintenance and long-term design.

## 2. Materials and Methods

### *2.1. Workflow*

We proposed a three-step workflow to quantify the long-term changes in the visual attributes of green spaces (Figure 1). These steps include (1) spatial data acquisition and

processing, (2) visual attribute quantification, and (3) visual attribute change analysis. We utilised unmanned aerial vehicles (UAVs) with five-axis tilt photography to obtain the point cloud models of urban green spaces during the summers of 2018 and 2023. By setting up viewpoints to generate panoramic images, we analysed the changes in multiple visual attribute indicators of 15 spatial samples over five years.

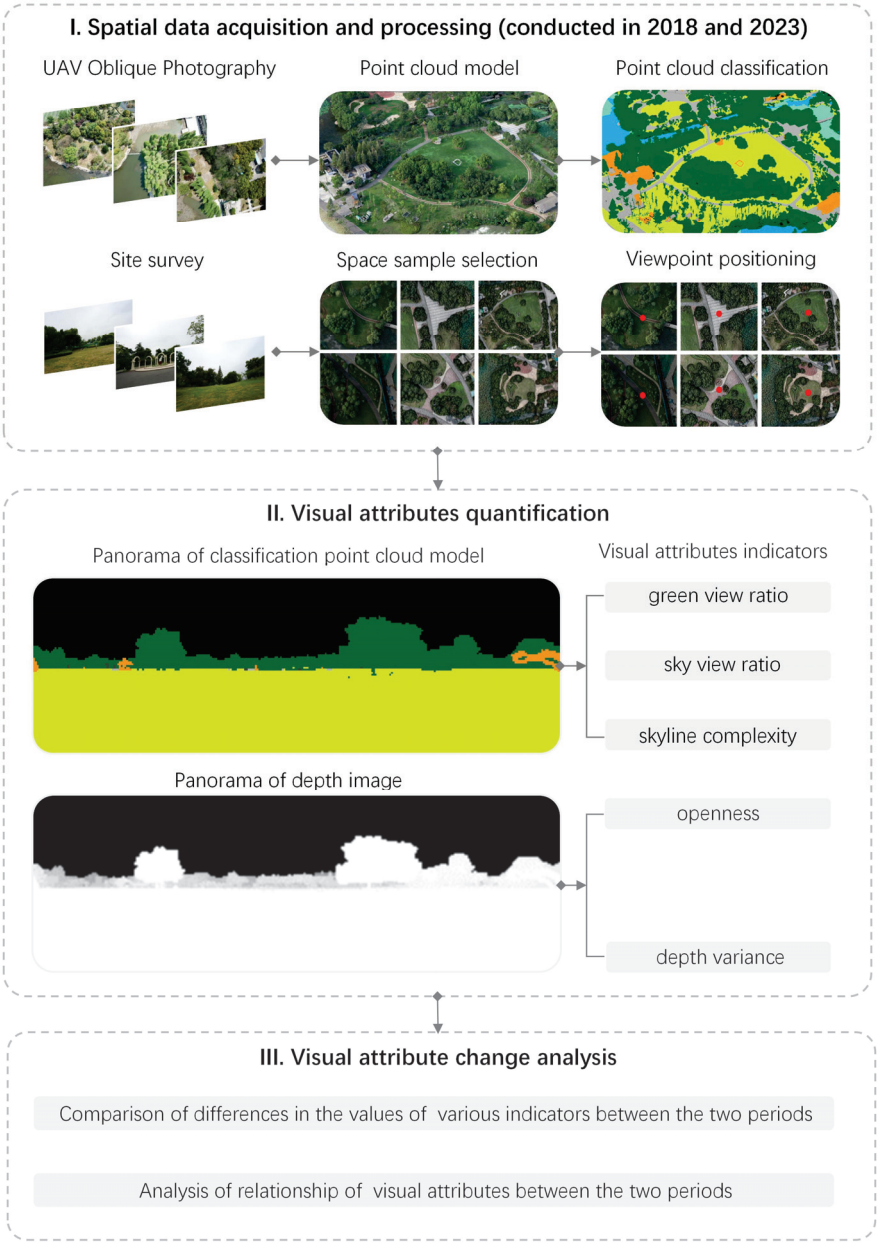



**Figure 1.** A workflow to analyse long-term changes in the visual attributes of urban green spaces. The red dots represent the location of the viewpoints of the spatial samples.

### *2.2. Study Area*

The study of long-term changes in the visual attributes of urban green spaces requires the continuous tracking of these spaces over a long period. It also necessitates that the study area remains in a maintained state without massive spatial layout changes. Qinglvyuan Park (QLY) in Nanjing, China, was selected as our study area (Figure 2).

**Figure 2.** Spatial sample selection of Qinglvyuan Park.

Nanjing is in the southeast coastal area of China, with a subtropical monsoon climate situation. QLY, a comprehensive urban park in the main city of Nanjing, was constructed in the 1960s and covers a total area of 30 hectares. It boasts diverse vegetation species and spatial patterns, making it a popular urban green space among residents who frequently utilise it for fitness and recreational activities.

We selected three types of landscape spatial samples, including lawns, paths, and plazas. Following a thorough site survey, we carefully selected 15 spatial samples for the study based on their representation of the typical characteristics of urban green spaces in China, with no drastic changes observed over the five years, and their status as active nodes frequented by people.

### *2.3. Data Collection and Processing*

The use of UAV five-axis tilt photography to acquire the three-dimensional spatial data of urban green spaces has been applied in various quantitative spatial morphology studies of urban spaces, offering distinct advantages in terms of data collection efficiency [42]. We conducted the aerial five-axis tilt photography of QLY in August 2018 and September 2023. Subsequently, the captured photos were imported into the DJI Terra 3.9.0 software to generate comprehensive 3D models, which were exported in a point cloud format.

To fulfil the requirements for analysing multiple visual indicators, we employed the outdoor point cloud classification tool within the Trimble Realworks 12.0 software to automatically classify the point cloud model. Following this automated classification, manual correction and secondary editing were conducted to refine the classification process. As a result, the point cloud model was classified into six distinct categories, namely vegetation (trees and shrubs), lawn areas, hard surfaces, water bodies, buildings, and facilities. Each category was assigned a different colour, and the point cloud models were finally assembled as the basis for subsequent analysis.

### *2.4. Visual Indicator Calculation*

We selected five indicators for analysis, including openness (OP), depth variance (DV), green view ratio (GVR), sky view ratio (SVR), and skyline complexity (SC), which are related to the three-dimensional and two-dimensional visual attributes of the urban green spaces. Referring to the method used by Tang et al. [39], we employed parameterised virtual cameras in the classified point cloud models to generate panoramic images integrated with spatial information. Additionally, we utilised depth images, which encode the visual distance between elements and the human eye through pixel colour information, as an effective means to study the 3D visual attributes of landscape space, such as openness and depth variance [22,43].

Firstly, we set the viewpoint positions and parameters in the classified point cloud models. A virtual viewpoint was placed in the centre of each spatial sample at a height of 1.6 m above the ground. The field of view for each viewpoint was set to 360° horizontally and 120° vertically. Secondly, using the visualisation function in the open-source C++ library PCL (point cloud library), we simulated the visual interfaces corresponding to each viewpoint to obtain panoramic images containing element classification information and panoramic depth images. Finally, by processing and analysing the resulting images, we could calculate the relevant visual attribute indicators (Table 1).

**Table 1.** Description and calculation of visual attribute indicators.

| Indicator | Reference | Description of Indicators | Equation | Note |
|---|---|---|---|---|
| Openness (OP) | [18] | OP is the average distance of elements within a person's visual field, indicating the person's perception of the visual scale. | $OP = \sum_{i=1}^{n} \frac{d_i}{n}$ | n is the number of pixels in the panorama, and $d_i$ is the depth value of each pixel. |
| Depth variance (DV) | [22] | DV is the variance of the depth values of the elements within a person's visual field, describing the complexity of the space in the longitudinal direction. | $DV = \sum_{i=1}^{n} \frac{(d_i - OP)^2}{n}$ | OP is the openness, n is the number of pixels in the panorama, and $d_i$ is the depth value of each pixel. |
| Green view ratio (GVR) | [21] | GVR is the proportion of vegetation in a person's visual field, describing the degree of naturalness of the space. | $GVR = \frac{S_V}{S_w}$ | $S_V$ is the area of vegetation in the panoramic image, and $S_w$ is the area in the panoramic image. |
| Sky view ratio (SVR) | [44] | SVR is the proportion of the area of the sky in a person's visual field, describing the visual scale of the space. | $SVR = \frac{S_s}{S_w}$ | $S_s$ is the area of the sky in the panoramic image, and $S_w$ is the area of the panoramic image. |
| Skyline complexity (SC) | [45] | SC is the ratio of the length of the skyline to the width of the visual interface, indicating the vertical complexity of spatial elements. | $SC = \frac{L_s}{L_w}$ | $L_s$ is the length of the skyline, and $L_w$ is the width of the panoramic image the panoramic image. |

### *2.5. Statistical Analysis*

Excel and SPSS were employed to analyse long-term changes in the five visual indicators across the fifteen spatial samples, as well as to explore differences in indicator values and the extent of change. The quantitative results of the visual attribute indicators were input into Excel, where they were visually analysed through the creation of bar charts. Furthermore, to investigate the potential for predicting future changes in the visual attributes of landscape spaces, we analysed the correlation between the change values of the visual indicators and their initial values. We derived the difference values of various indicators before and after five years (d_OP, d_DV, d_GVR, d_SVR and d_SC). Subsequently, the Spearman correlation analysis tool within SPSS was utilised to examine the correlation between these difference values and the respective indicator values as of 2018.

## 3. Results

### *3.1. Comparison of Point Cloud Models before and after Five Years*

Given that changes in the physical form of the landscape space are prerequisites to alterations in visual attributes, we initially investigated differences in the point cloud model of QLY before and after the five years (Figure 3). Upon the examination of the classified point cloud models, it became apparent that the overall spatial pattern of the park remained relatively stable. The main changes were the new buildings inside the park and the increase in some vegetation. Notable changes include the conversion of a densely wooded area in the central part of the park into a landscaped building and the establishment of a new shopping street in the southeast corner of the park. Additionally, shrubs were planted on some open lawns.

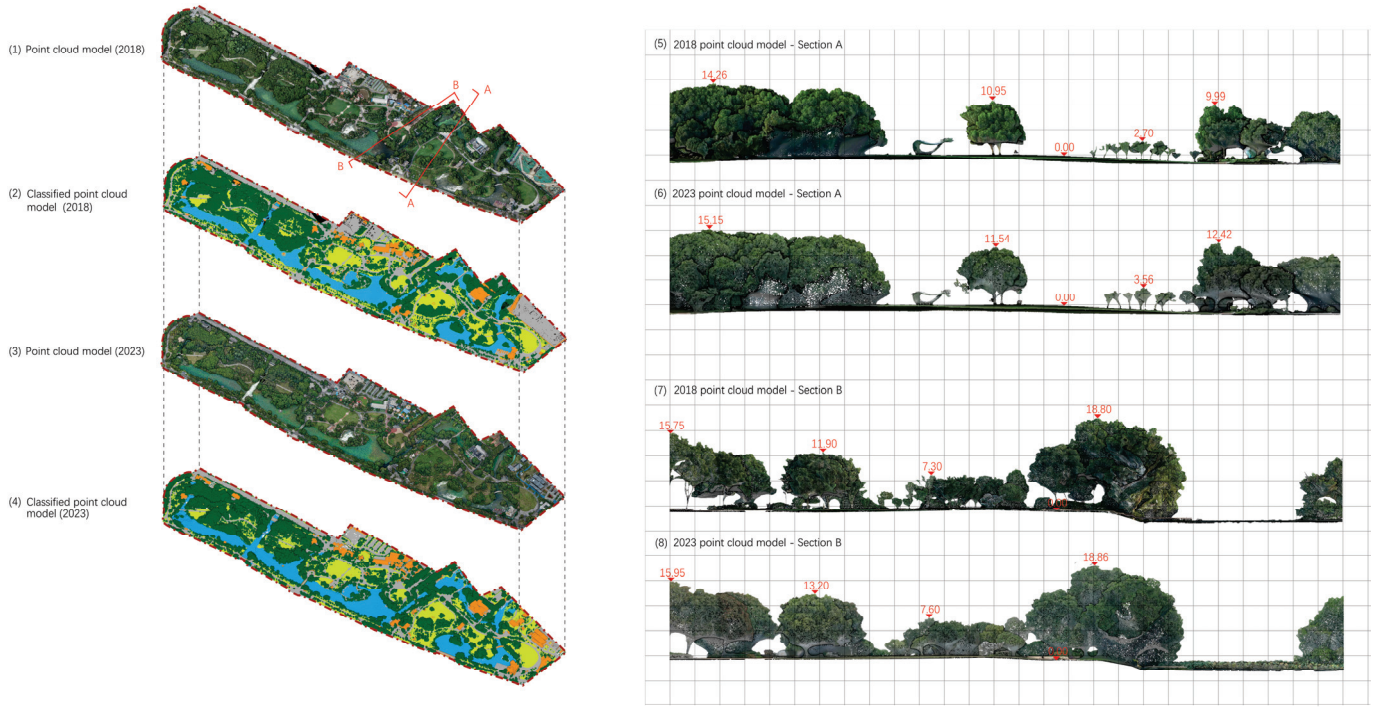



**Figure 3.** Differences between the point cloud models of the two periods.

In addition to these artificial renovations, changes in vegetation form over the five-year period also influence the visual characteristics of green spaces. We delved into the subtle changes in vegetation form by investigating two sections of the central area of QLY. Overall, the trees experienced an increase in height over the five years, with the highest increase recorded at 2.43 m. There was considerable variation in the extent of height growth among individual trees. For instance, in Section A, which encompasses the lawn area in the park centre, the trees exhibited a height increase from 10.95 m in 2018 to 11.55 m in 2023, marking a growth of 0.6 m. However, there was a notable disparity in the growth rate of trees on either side of the lawn. Specifically, the taller trees on the left side experienced a height increase of 0.89 m, while the shorter trees on the right side saw a height increase of 2.43 m. Similar disparities in tree height growth were observed in Section B. While the trees in the middle of Section B increased in height from 11.9 to 13.2 m, the taller trees on either side experienced marginal height increases of 0.2 and 0.06 m.

### *3.2. Changes in Visual Attributes before and after Five Years*

Figure 4 illustrates the results of the analysis of the five visual attribute indicators across the 15 samples. In general, all the indicators exhibited some degree of change after five years. Although there are variations in the extent of changes between the indicators,

there are some similarities in the changes in the visual features across the samples. For example, OP, DV, and SVR generally decreased, while GVR increased after five years.

**Figure 4.** Comparison of visual attribute indicators before and after five years.

(1) Changes in openness (OP)

The openness of all the samples decreased over the five-year period except for sample A1 (Figure 4a–c). This exception may be attributed to the construction of its eastern bare side as a commercial street area. Notably, the lawn samples exhibited higher openness values compared to the path and plaza samples in 2018. For example, in 2018, the openness of the lawn samples was [82.4, 97.3] (Figure 4a), while the distribution interval of openness values for the path and plaza samples was [60.9, 86.6] (Figure 4b,c). However, after five years, the lawn samples experienced the lowest reduction in openness. The path and plaza samples, on the other hand, demonstrated greater reductions in openness values, with

sample B4 exhibiting the most significant reduction, from 68.8 to 59.9, indicating a decrease of 12.8% (Figure 4b).

(2) Changes in depth variance (DV)

Similar to openness, changes in depth variance exhibited an overall declining trend (Figure 4d–f). Individual samples showed notable changes, such as a 10% decrease in sample B4 (Figure 4e). The rest of the samples showed decreases of less than 6%. The changes in DV values for the lawn samples were minor compared to the path and plaza samples.

(3) Changes in green view ratio (GVR)

All the samples demonstrated an increase in GVR after five years except for sample A1 (Figure 4g–i). The decrease in vegetation and increase in architectural elements in sample A1 were attributed to the removal of some trees at the edge of the lawn. The magnitude of changes in GVR did not significantly differ among the three types of spatial samples. The largest increases were observed in samples A3 (16.1%), B5 (26.6%), and C3 (23.1%). These changes were primarily driven by alterations in vegetation. Samples A3 (Figure 4g) and B5 (Figure 4h) experienced an increase in shrub planting on the lawn in 2023, while sample C (Figure 4i) witnessed an increase in the canopy width of trees around the plaza.

(4) Changes in sky view ratio (SVR)

The changes in SVR exhibited a trend nearly opposite to that of GVR, with sky coverage decreasing after five years for all the samples except A1 (Figure 4j–l). However, compared to the changes in GVR, the decrease in SVR was relatively smaller. For instance, sample B4 experienced the largest decrease of 14.6% (Figure 4k). The lawn and plaza samples showed reductions in SVR values of less than 4% and 10%. It is notable that the distribution of SVR values and the changes in SVR for each sample mirrored those of OP, but the decrease in OP values was more pronounced. This discrepancy could be attributed to the growth of tree canopies in both vertical and horizontal dimensions over the five-year period, which reduced the distance between the canopy surface and observers, consequently reducing the area of sky visible in people's field of view.

(5) Changes in skyline complexity (SC)

The changes in SC presented significant differences from the other indicators, as the samples did not exhibit a uniform increase or decrease trend in values (Figure 4m–o). Variations in changes were observed among different types of samples. For instance, the SC of the plaza samples uniformly decreased, while the path samples demonstrated an increase in value for all the samples except B1, and the lawn samples displayed both increases and decreases in value. Regarding the magnitude of change, samples A1 (Figure 4m) and B1 (Figure 4n) exhibited the largest changes of 21.4% and 21.6%. The decrease in SC for sample A1 was primarily due to the replacement of trees on the fringe of the lawn with new buildings. In contrast, the trees on the border of sample B1 experienced growth over the five-year period, resulting in canopy connectivity and a decrease in SC.

### *3.3. Correlation of the Changed and Initial Values of Indicators*

Table 2 depicts the results of a Spearman correlation analysis of the changes in visual characteristic indicators compared to their initial values from five years ago. A negative correlation is observed between SC and d_SC, with a correlation coefficient of $-0.545$. However, correlations between SC and d_SC and the other indicators are notably weak. Additionally, correlations are observed between GVR and d_GVR, and SVR and d_GVR, with the correlation coefficients of 0.518 and $-0.611$, respectively. d_GVR and GRV show a positive correlation, while d_GVR and SVR show a negative correlation. This suggests that when there are more green plants in the landscape space, the growth rate of GVR may also be higher.

**Table 2.** Spearman correlation analysis of the changes in visual indicators compared to their initial values.

| | OP | DV | GVR | SVR | SC |
|---|---|---|---|---|---|
| **d_OP** | 0.489 (0.064 *) | 0.371 (0.173) | −0.282 (0.308) | 0.329 (0.232) | −0.275 (0.321) |
| **d_DV** | 0.496 (0.060 *) | 0.382 (0.160) | −0.286 (0.302) | 0.332 (0.226) | −0.3 (0.277) |
| **d_GVR** | −0.389 (0.152) | −0.225 (0.420) | 0.518 (0.048 **) | −0.611 (0.016 **) | 0.025 (0.930) |
| **d_SVR** | 0.229 (0.413) | 0.086 (0.761) | −0.279 (0.315) | 0.421 (0.118) | 0.000 (1.000) |
| **d_SC** | −0.013 (0.965) | 0.009 (0.975) | 0.036 (0.899) | 0.084 (0.766) | −0.545 (0.036 **) |

Notes: ** $p \leq 0.05$, * $p \leq 0.1$.

## 4. Discussion

### *4.1. Confirming the Long-Term Changes in Visual Attributes of Urban Green Spaces*

Quantitatively describing the visual attributes of landscape space through visual indicators plays a role in assessing the quality of landscape space and supporting landscape design [13,22,46]. For example, previous studies have experimentally confirmed people's preference for landscape spaces with a high level of openness or complexity [19,47]. Although these thresholds on landscape visual indicators provide a reference for designers in urban green space design, achieving landscape spaces that align precisely with these findings is not always straightforward. As illustrated by Ode et al. [26] and demonstrated in this paper, the visual attributes of landscape spaces can change over a long period. Factors such as the growth and death of plants, as well as artificial pruning and renovation, all contribute to the change in visual attributes.

The findings of this study confirm that the visual attributes of urban green spaces undergo changes over a five-year period, with certain indicators experiencing notable fluctuations. Among all the samples, the maximum decrease in OP is 12.8%, and the maximum increase in GVR is 26.6%. This means that the same landscaped space may have deteriorated in spatial quality over a five-year period, which in turn may affect the vitality of the space and the activities of people [48]. For instance, Jiang et al. found that green spaces provide the highest degree of stress-relieving benefits to men when the percentage of trees in the field of view is 24–34% [49]. Sample B5 had a GVR of 28% in 2018 and 35.4% in 2023, exceeding the threshold range proposed by Jiang et al. This suggests that the monitoring of dynamic changes in the visual attributes of urban green spaces can provide some decision-making support for the management of green spaces. However, we do not know whether changes in the visual character of the same landscape space can lead to a significant reduction in landscape preference for residents who regularly spend time in the green space since factors such as familiarity with the landscape environment can also influence landscape preference [50].

The use of photographs in the studies of landscape change allows the rapid documentation of spatial change, but in addition to the requirements for the angle and position of the photographs, it is difficult to analyse the spatial depth and other three-dimensional visual features. For example, Hammond et al. found that the similarity of the photographs before and after two years was around 90% by calculating the similarity of the pictures after repeating the photographs at the same location in 2015, 2016, and 2017 [51]. Li showed by analysing the Google Street View images of New York City that the mean Green View Index of the study area increased from 19.33 to 19.77 from 2008–2013 to 2014–2018 [52]. Point clouds can not only accurately and intuitively show the changes in the spatial form of green spaces but also help in analysing 2D and 3D visual attributes [17]. In our analyses of multiple spatial samples in QLY, we not only analysed the changes in the visual attributes of each sample but also found that different types of spatial samples exhibit variations in the changes in various indicators. For instance, for OP and DV, the lawn samples showed a lower magnitude of change than the path and plaza samples. This could be difficult to achieve with the use of 2D images.

Similar to recording and understanding landscape changes through photographs taken over time [53,54], we can record spatial information of urban green spaces through

a repeated collection of point clouds in order to understand the changes in their visual attributes. In response to these changes, appropriate management strategies such as tree pruning can be developed to meet the needs of sustainability and conform to people's preferences.

### *4.2. Potential for Predicting Long-Term Changes in Visual Attributes of Urban Green Spaces*

Grêt-Regamey and Fagerholm proposed that we need to use 3D digital environments to support an adaptive process between people's perceptions and planning proposals [55]. When our tools are unable to consider short- and long-term spatial and temporal dynamics, it will be difficult to propose effective novel governance strategies. By constructing a 3D visualisation platform, some studies developed a more realistic vision of the landscape design scheme and how the vision may change over time [56,57]. However, the dynamics of these platforms are often realised by applying a single rule of shape change to the same species of tree. The results of this study suggest that the spatial form and visual attributes of urban green spaces may show a more complex variation.

We hope to explore the potential for predicting changes in the visual attributes of urban green spaces. As shown in the results, certain correlations exist between some of the indicators. For example, the change in GVR may be related to the initial GVR and SVR. Notably, a strong negative correlation exists between changes in SC and the initial value, while correlations with other visual characteristic indicators are weak. However, we found that the variety of changes in the form of individual trees posed challenges in accurately discerning the mechanism of correlation between indicators. For instance, considering SC, its value was higher when trees had smaller crowns and gaps between each other in the early stages. As trees grew and canopies expanded, multiple canopies may eventually connect, leading to a decrease in SC. Additionally, differences in the growth rates of different trees further influenced changes in SC.

Studies have demonstrated that tree growth rates are influenced by various factors, including tree size, age, competition with neighbouring trees, and environmental conditions [58]. With advancements in fields such as forestry, growth simulation and shape prediction of trees have become possible [28,29,59]. The realisation of tree growth prediction will contribute to the exploration of the dynamics of the visual attributes of urban green spaces. Furthermore, when viewed over a long period of time, elemental changes in landscape space tend to receive the influence of more complex factors. For example, Roman et al. [60] analysed changes in tree canopy cover on a university campus through a combination of archival records and aerial imagery and found that the trees on campus were influenced by a combination of planting actions and management approaches, urban greening and city planning movements, and university faculty. Therefore, future studies on predicting long-term changes in the visual attributes of urban green spaces need to focus on the links between the properties of trees and their environmental conditions. Additionally, they should investigate the mechanisms of changes in visual attributes over longer time spans and with multiple recorded sources.

### *4.3. Limitations*

This study utilised UAV 5-axis photography for collecting spatial data on urban green spaces. This method lacks data acquisition for the bottom layer of the canopy, which is often too dense to capture from aerial perspectives, resulting in difficulties in obtaining accurate information about tree trunks and branches. Future studies could consider obtaining more precise and complete point cloud models using ground-based or mobile LiDAR scanning, potentially aiding in predicting tree growth.

Additionally, our choice of QLY, established in the 1960s, as our study area means that most trees in the park are relatively old. As the growth rate of trees correlates with their age, the results of our study may not be directly applicable to parks with more recent construction dates. Moreover, the on-site pruning and maintenance of vegetation conducted by gardeners posed challenges in obtaining the records of manual maintenance

over the five-year period. Although we could infer changes in vegetation volume through point cloud modelling, we lacked information regarding whether these changes resulted from manual pruning. In the future, conducting long-term tracking surveys of urban green spaces and recording more comprehensive maintenance information could support the in-depth studies of changes in the visual attributes of urban green spaces.

## 5. Conclusions

The visual attribute of urban green space is one of the most important factors in shaping the quality of landscape space and influencing people's landscape preferences. However, previous studies often overlook the dynamic changes in landscape spaces, potentially hindering the applicability of their findings to design and maintenance practices.

This study proposed a novel approach using point clouds to examine the long-term changes in the visual attributes of urban green spaces, with a focus on a comprehensive urban park in Nanjing, China. Our investigation reveals that there could be considerable changes in visual indicators such as the green visual ratio (GVR) and the openness (OP) of urban green spaces. Although there is a correlation between indicators, such as skyline complexity (SC) and its change (d_SC), and between GVR and its change d_GVR, it is still difficult to accurately describe the changing patterns and influencing factors. It is concluded that monitoring and analysing the long-term changes in the visual attributes of urban green spaces can support sustainable maintenance and design strategies. Future research could explore the evolving patterns of these visual attributes over extended timeframes and incorporate more diverse data sources based on the accurate simulation of the dynamic changes in trees and other environmental elements.

Despite some limitations, this study demonstrates the feasibility of exploring long-term changes in the visual attributes of urban green spaces using point clouds. This approach may be useful for exploring the dynamic changes in landscape space in the future.

**Author Contributions:** Conceptualisation, X.Z.; methodology, X.Z.; software, S.C.; formal analysis, X.Z. and Y.F; investigation, X.Z.; resources, S.C. and X.Z.; data curation, X.Z. and Y.F.; writing—original draft preparation, X.Z. and Y.F; writing—review and editing, S.C. and G.Z.; visualisation, X.Z. and Y.F; funding acquisition, S.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Fundamental Research Funds for the Central Universities, grant number 2242021R20016; Jiangsu Planned Projects for Postdoctoral Research Funds, grant number 2021K024A; China Postdoctoral Science Foundation, grant number 2021M700767; China Postdoctoral Science Foundation, grant number 2022T150115; National Natural Science Foundation of China, grant number 52108045; The Scholarship for Visiting Scholars of Key Laboratory of New Technology for Construction of Cities in Mountain Area, grant number LNTCCMA-20240106 and China Scholarship Council, grant number 202206090038.

**Data Availability Statement:** The datasets presented in this article are not readily available because the data are part of an ongoing study. Requests to access the datasets should be directed to the corresponding author.

**Acknowledgments:** We would like to thank Yuanfei Ma for his support in software and equipment, Chaoming Li and Yijing Wang for their technical assistance in the point cloud data acquisition and processing and Yuning Cheng for his support throughout this study.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Lam, W.W.Y.; Loo, B.P.Y.; Mahendran, R. Neighbourhood environment and depressive symptoms among the elderly in Hong Kong and Singapore. *Int. J. Health Geogr.* **2020**, *19*, 48. [CrossRef] [PubMed]
2. Reuben, A.; Rutherford, G.W.; James, J.; Razani, N. Association of neighborhood parks with child health in the United States. *Prev. Med.* **2020**, *141*, 106265. [CrossRef] [PubMed]
3. Vassos, E.; Agerbo, E.; Mors, O.; Pedersen, C.B. Urban–rural differences in incidence rates of psychiatric disorders in Denmark. *Br. J. Psychiatry* **2016**, *208*, 435–440. [CrossRef] [PubMed]

4. Chen, T.; Lang, W.; Li, X. Exploring the impact of urban green space on residents' health in Guangzhou, China. *J. Urban Plan. Dev.* **2020**, *146*, 05019022. [CrossRef]
5. Duan, J.; Wang, Y.; Fan, C.; Xia, B.; de Groot, R. Perception of urban environmental risks and the effects of urban green infrastructures (UGIs) on human well-being in four public green spaces of Guangzhou, China. *Environ. Manag.* **2018**, *62*, 500–517. [CrossRef] [PubMed]
6. Madureira, H.; Nunes, F.; Oliveira, J.V.; Cormier, L.; Madureira, T. Urban residents' beliefs concerning green space benefits in four cities in France and Portugal. *Urban For. Urban Green.* **2015**, *14*, 56–64. [CrossRef]
7. Alcock, I.; White, M.P.; Wheeler, B.W.; Fleming, L.E.; Depledge, M.H. Longitudinal Effects on Mental Health of Moving to Greener and Less Green Urban Areas. *Environ. Sci. Technol.* **2014**, *48*, 1247–1255. [CrossRef] [PubMed]
8. Chen, Y.; Liu, T.; Xie, X.; Marusic, B.G. What Attracts People to Visit Community Open Spaces? A Case Study of the Overseas Chinese Town Community in Shenzhen, China. *Int. J. Environ. Res. Public Health* **2016**, *13*, 644. [CrossRef]
9. Polat, A.T.; Akay, A. Relationships between the visual preferences of urban recreation area users and various landscape design elements. *Urban For. Urban Green.* **2015**, *14*, 573–582. [CrossRef]
10. Appleton, J. *The Experience of Landscape*; Wiley: Hoboken, NJ, USA, 1996.
11. Kaplan, R.; Kaplan, S. *The Experience of Nature: A Psychological Perspective*; Cambridge University Press: Cambridge, UK, 1989.
12. Grahn, P.; Stigsdotter, U.K. The relation between perceived sensory dimensions of urban green space and stress restoration. *Landsc. Urban Plan.* **2010**, *94*, 264–275. [CrossRef]
13. Tveit, M.; Ode, Å.; Fry, G. Key concepts in a framework for analysing visual landscape character. *Landsc. Res.* **2006**, *31*, 229–255. [CrossRef]
14. Purcell, A.T.; Lamb, R.J. Preference and naturalness: An ecological approach. *Landsc. Urban Plan.* **1998**, *42*, 57–66. [CrossRef]
15. Susaki, J.; Kubota, S. Automatic Assessment of Green Space Ratio in Urban Areas from Mobile Scanning Data. *Remote Sens.* **2017**, *9*, 215. [CrossRef]
16. Wu, J.; Lu, J. Spatial scale effects of landscape metrics on stream water quality and their seasonal changes. *Water Res.* **2021**, *191*, 116811. [CrossRef] [PubMed]
17. Qi, J.; Lin, E.S.; Yok Tan, P.; Chun Man Ho, R.; Sia, A.; Olszewska-Guizzo, A.; Zhang, X.; Waykool, R. Development and application of 3D spatial metrics using point clouds for landscape visual quality assessment. *Landsc. Urban Plan.* **2022**, *228*, 104585. [CrossRef]
18. Zhao, Y.; Wu, B.; Wu, J.; Shu, S.; Liang, H.; Liu, M.; Badenko, V.; Fedotov, A.; Yao, S.; Yu, B. Mapping 3D visibility in an urban street environment from mobile LiDAR point clouds. *GIScience Remote. Sens.* **2020**, *57*, 797–812. [CrossRef]
19. Zhang, G.; Yang, J.; Wu, G.; Hu, X. Exploring the interactive influence on landscape preference from multiple visual attributes: Openness, richness, order, and depth. *Urban For. Urban Green.* **2021**, *65*, 127363. [CrossRef]
20. Sugiyama, T.; Thompson, C.W. Older people's health, outdoor activity and supportiveness of neighbourhood environments. *Landsc. Urban Plan.* **2007**, *83*, 168–175. [CrossRef]
21. Zhu, H.; Yang, F.; Bao, Z.; Nan, X. A study on the impact of Visible Green Index and vegetation structures on brain wave change in residential landscape. *Urban For. Urban Green.* **2021**, *64*, 127299. [CrossRef]
22. Zhang, X.; Lin, E.S.; Tan, P.Y.; Qi, J.; Waykool, R. Assessment of visual landscape quality of urban green spaces using image-based metrics derived from perceived sensory dimensions. *Environ. Impact Assess. Rev.* **2023**, *102*, 107200. [CrossRef]
23. Clark, P.E.; Hardegree, S.P. Quantifying Vegetation Change by Point Sampling Landscape Photography Time Series. *Rangel. Ecol. Manag.* **2005**, *58*, 588–597. [CrossRef]
24. Kienast, F.; Frick, J.; van Strien, M.J.; Hunziker, M. The Swiss Landscape Monitoring Program—A comprehensive indicator set to measure landscape change. *Ecol. Model.* **2015**, *295*, 136–150. [CrossRef]
25. Liu, T.; Yang, X. Monitoring land changes in an urban area using satellite imagery, GIS and landscape metrics. *Appl. Geogr.* **2015**, *56*, 42–54. [CrossRef]
26. Ode, Å.; Tveit, M.S.; Fry, G. Advantages of using different data sources in assessment of landscape change and its effect on visual scale. *Ecol. Indic.* **2010**, *10*, 24–31. [CrossRef]
27. Smardon, R.C. Perception and aesthetics of the urban environment: Review of the role of vegetation. *Landsc. Urban Plan.* **1988**, *15*, 85–106. [CrossRef]
28. Rotzer, T.; Rahman, M.A.; Moser-Reischl, A.; Pauleit, S.; Pretzsch, H. Process based simulation of tree growth and ecosystem services of urban trees under present and future climate conditions. *Sci. Total. Environ.* **2019**, *676*, 651–664. [CrossRef]
29. Vaz Monteiro, M.; Levanič, T.; Doick, K.J. Growth rates of common urban trees in five cities in Great Britain: A dendrochronological evaluation with an emphasis on the impact of climate. *Urban For. Urban Green.* **2017**, *22*, 11–23. [CrossRef]
30. Yang, J.; Zhang, M.; Zhang, J.; Lu, H.; Hauer, R.J. Allometric Growth of Common Urban Tree Species in Qingdao City of Eastern China. *Forests* **2023**, *14*, 472. [CrossRef]
31. Speak, A.F.; Salbitano, F. The impact of pruning and mortality on urban tree canopy volume. *Urban For. Urban Green.* **2023**, *79*, 127810. [CrossRef]
32. Duryea, M.L.; Blakeslee, G.M.; Hubbard, W.G.; Vasquez, R.A. Wind and trees: A survey of homeowners after Hurricane Andrew. *J. Arboric.* **1996**, *22*, 44–50. [CrossRef]
33. Zhao, W.; Zhang, L.; Li, X.; Peng, L.; Wang, P.; Wang, Z.; Jiao, L.; Wang, H. Residents' Preference for Urban Green Space Types and Their Ecological-Social Services in China. *Land* **2022**, *11*, 2239. [CrossRef]

34. Walz, U. Monitoring of landscape change and functions in Saxony (Eastern Germany)—Methods and indicators. *Ecol. Indic.* **2008**, *8*, 807–817. [CrossRef]
35. Bayr, U. Quantifying historical landscape change with repeat photography: An accuracy assessment of geospatial data obtained through monoplotting. *Int. J. Geogr. Inf. Sci.* **2021**, *35*, 2026–2046. [CrossRef]
36. Walz, U.; Hoechstetter, S.; Drăguţ, L.; Blaschke, T. Integrating time and the third spatial dimension in landscape structure analysis. *Landsc. Res.* **2015**, *41*, 279–293. [CrossRef]
37. Larkin, A.; Hystad, P. Evaluating street view exposure measures of visible green space for health research. *J. Expo. Sci. Environ. Epidemiol.* **2019**, *29*, 447–456. [CrossRef]
38. Yang, Y.; Lu, Y.; Yang, H.; Yang, L.; Gou, Z. Impact of the quality and quantity of eye-level greenery on park usage. *Urban For. Urban Green.* **2021**, *60*, 127061. [CrossRef]
39. Tang, L.; He, J.; Peng, W.; Huang, H.; Chen, C.; Yu, C. Assessing the visibility of urban greenery using MLS LiDAR data. *Landsc. Urban Plan.* **2023**, *232*, 104662. [CrossRef]
40. Urech PR, W.; Dissegna, M.A.; Girot, C.; Grêt-Regamey, A. Point cloud modeling as a bridge between landscape design and planning. *Landsc. Urban Plan.* **2020**, *203*, 103903. [CrossRef]
41. Xiao, W.; Cao, H.; Tang, M.; Zhang, Z.; Chen, N. 3D urban object change detection from aerial and terrestrial point clouds: A review. *Int. J. Appl. Earth Obs. Geoinf.* **2023**, *118*, 103258. [CrossRef]
42. Yijing, W.; Yuning, C. Construction and analysis of 3D scene model of landscape space based on UAV oblique photography and 3D laser scanner. *J. Digit. Landsc. Archit.* **2018**, *3*, 283–290.
43. Yokoya, N.; Nakazawa, S.; Matsuki, T.; Iwasaki, A. Fusion of hyperspectral and LiDAR data for landscape visual quality assessment. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2014**, *7*, 2419–2425. [CrossRef]
44. Wang, R.; Jiang, W.; Lu, T. Landscape characteristics of university campus in relation to aesthetic quality and recreational preference. *Urban For. Urban Green.* **2021**, *66*, 127389. [CrossRef]
45. Hu, T.; Wei, D.; Su, Y.; Wang, X.; Zhang, J.; Sun, X.; Liu, Y.; Guo, Q. Quantifying the shape of urban street trees and evaluating its influence on their aesthetic functions based on mobile lidar data. *ISPRS J. Photogramm. Remote. Sens.* **2022**, *184*, 203–214. [CrossRef]
46. Huang, J.; Liang, J.; Yang, M.; Li, Y. Visual Preference Analysis and Planning Responses Based on Street View Images: A Case Study of Gulangyu Island, China. *Land* **2022**, *12*, 129. [CrossRef]
47. Liu, Q.; Zhu, Z.; Zeng, X.; Zhuo, Z.; Ye, B.; Fang, L.; Huang, Q.; Lai, P. The impact of landscape complexity on preference ratings and eye fixation of various urban green space settings. *Urban For. Urban Green.* **2021**, *66*, 127411. [CrossRef]
48. Wang, M.; Qiu, M.; Chen, M.; Zhang, Y.; Zhang, S.; Wang, L. How does urban green space feature influence physical activity diversity in high-density built environment? An on-site observational study. *Urban For. Urban Green.* **2021**, *62*, 127129. [CrossRef]
49. Jiang, B.; Chang, C.-Y.; Sullivan, W.C. A dose of nature: Tree cover, stress reduction, and gender differences. *Landsc. Urban Plan.* **2014**, *132*, 26–36. [CrossRef]
50. Mangone, G.; Dopko, R.L.; Zelenski, J.M. Deciphering landscape preferences: Investigating the roles of familiarity and biome types. *Landsc. Urban Plan.* **2021**, *214*, 104189. [CrossRef]
51. Hammond, W.M.; Stone ME, B.; Stone, P.A. Picture worth a thousand words: Updating repeat photography for 21st century ecologists. *Ecol. Evol.* **2020**, *10*, 14113–14121. [CrossRef]
52. Li, X. Examining the spatial distribution and temporal change of the green view index in New York City using Google Street View images and deep learning. *Environ. Plan. B Urban Anal. City Sci.* **2020**, *48*, 2039–2054. [CrossRef]
53. Cerney, D.L. The use of repeat photography in contemporary geomorphic studies: An evolving approach to understanding landscape change. *Geogr. Compass* **2010**, *4*, 1339–1357. [CrossRef]
54. Millington, J.A.; Booth, C.A.; Fullen, M.A.; Moore, G.M.; Trueman, I.C.; Worsley, A.T.; Richardson, N.; Baltrenaite, E. The role of long-term landscape photography as a tool in dune management. *J. Environ. Eng. Landsc. Manag.* **2009**, *17*, 253–260. [CrossRef]
55. Grêt-Regamey, A.; Fagerholm, N. Key factors to enhance efficacy of 3D digital environments for transformative landscape and urban planning. *Landsc. Urban Plan.* **2024**, *244*, 104978. [CrossRef]
56. Lange, E.; Hehl-Lange, S. Making visions visible for long-term landscape management. *Futures* **2010**, *42*, 693–699. [CrossRef]
57. Yu, H.; Wu, M.M.; He, H.S. Developing platform of 3-D visualization of forest landscape. *Environ. Model. Softw.* **2022**, *157*, 105524. [CrossRef]
58. Zhang, Z.; Papaik, M.J.; Wang, X.; Hao, Z.; Ye, J.; Lin, F.; Yuan, Z. The effect of tree size, neighborhood competition and environment on tree growth in an old-growth temperate forest. *J. Plant Ecol.* **2017**, *10*, 970–980. [CrossRef]
59. Hu, X.; Zhang, H.; Yang, G.; Qiu, H.; Lei, K.; Yang, T.; Liu, Y.; Zuo, Y.; Wang, J.; Cui, Z. Visual Simulation Research on Growth Polymorphism of Chinese Fir Stand Based on Different Comprehensive Grade Models of Spatial Structure Parameters. *Forests* **2023**, *14*, 617. [CrossRef]
60. Roman, L.A.; Fristensky, J.P.; Eisenman, T.S.; Greenfield, E.J.; Lundgren, R.E.; Cerwinka, C.E.; Hewitt, D.A.; Welsh, C.C. Growing Canopy on a College Campus: Understanding Urban Forest Change through Archival Records and Aerial Photography. *Environ. Manag.* **2017**, *60*, 1042–1061. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

land

MDPI

*Article*

# Exploring the Relationships between Mini Urban Green Space Layout and Human Activity

**Shi Cheng [1,2], Dunsong Zhang [1], Yijing Wang [3] and Xiaohan Zhang [4,*]**

[1] Department of Architecture, Southeast University, Nanjing 210096, China; 101300063@seu.edu.cn (S.C.); 213193556@seu.edu.cn (D.Z.)
[2] Chinese National Visual Image Research Base, Southeast University, Nanjing 210096, China
[3] College of Architecture, Nanjing Tech University, Nanjing 211816, China; yijingwang@njtech.edu.cn
[4] Department of Architecture, Technical University of Munich, 80333 Munich, Germany
* Correspondence: xiao-han.zhang@tum.de

**Abstract:** The quality of urban green space has an impact on the health and well-being of populations. Previous studies have shown that consideration of crowd activity characteristics is the key premise of landscape space design and planning. However, there is limited research on the correlation between features of the spatial layout of Mini Urban Green Spaces (MUGS) and the behavior of people, and it is difficult to take into account the possible distribution of people and their activity characteristics during the design phase of MUGS. This study aims to construct a technical workflow utilizing the AnyLogic platform and agent-based simulation methods for analyzing the characteristics of landscape spatial layouts considering dynamic human behavior. One MUGS, named 511 Park in Nanjing, China, was selected as the case for the application of the method and exploration of the impacts of spatial elements and layout on crowd activity types and density. We investigated the impact of four types of spatial elements—paths, facilities, nodes, and entrances—on human activities in MUGS. The results showed that path layout emerged as the most significant influencing factor. Changes in nodes and the number of facilities have a relatively minor impact on people's activities. There was an apparent impact of changes in path orientation around nodes on the dynamics of the flow of people. This study could provide valuable insights for landscape designers, aiding informed decision-making during the construction, renovation, and management of MUGS.

**Keywords:** Mini Urban Green Spaces; spatial layout; human activity; behavior simulation; agent-based modeling

**Citation:** Cheng, S.; Zhang, D.; Wang, Y.; Zhang, X. Exploring the Relationships between Mini Urban Green Space Layout and Human Activity. *Land* **2024**, *13*, 871. https://doi.org/10.3390/land13060871

Academic Editor: Maria Rosa Trovato

Received: 30 April 2024
Revised: 3 June 2024
Accepted: 10 June 2024
Published: 17 June 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

### *1.1. Definition and Significance of Mini Urban Green Space*

As a result of urbanization, most densely populated cities worldwide have recognized the invaluable role of physical exercise in promoting health and well-being [1,2]. Urban green spaces provide opportunities for citizens to immerse themselves in nature and engage in physical activities essential for a healthy lifestyle [3,4]. The urban built environment is interspersed with numerous Mini Urban Green Spaces (MUGS) [4–6]. Compared to large-scale green spaces, MUGS are the most accessible outdoor spaces for residents' daily exercise and recreation and are better integrated into their surroundings and context. In densely populated urban areas, these intricately distributed MUGS provide more opportunities for people to interact with nature [4,7–10].

Studies on MUGS (often referred to as "pocket parks") are mainly geographically dominated in the Americas, China, and the European region [11,12]. Since the scale of MUGS lacks a precise universal definition, drawing from descriptions provided in publicly official documents, several types of MUGS can be summarized as shown in Table 1 [13–16]. In China, there is no explicit definition of the size range for MUGS within the national standard for green spaces, with requirements often varying by province and city. This

study adopts the definition of MUGS as outlined in the "Nanjing Pocket Park Construction Guidelines (Trial)", which specifies that the area of a MUGS (pocket park) should be less than 1 hectare ($hm^2$) [17–20].

**Table 1.** Various descriptions of mini green spaces.

| Country | Year | Name | Area/$hm^2$ | Source |
|---|---|---|---|---|
| United States | 1965 | Playlot | 0.02~0.45 | Standards for outdoor recreational areas |
| | | Playground | 0.8~2.8 | |
| | 2020 | Pocket park | ≤0.4 | Pocket park toolkit |
| United Kingdom | 2004 | Pocket park | ≤0.4 | The London plan, spatial development strategy for Greater London |
| Australia | 2008 | Pocket park | 0.25~1 | Western Precinct open space and landscape masterplan |
| China | 2002 | Small garden | 0.4~1 | Code of urban Residential Areas Planning & Design (GB 50180-93) |
| | 2014 | Neighborhood park | 0.4~1 | Standard for greening of residential districts and companies in Jiangsu province |
| | 2022 | Pocket park | ≤1 | POCKET PARK GUIDANCE OF JIANGSU (Trial 2022) |
| | 2023 | Pocket park | ≤1 | POCKET PARK GUIDANCE OF NANJING (Trial) |

Previous studies have indicated that exposure to green spaces positively mitigates issues such as low blood pressure and negative emotions [21,22] and promotes psychophysical health [2,10,23,24]. Researchers have further pointed out that green spaces within high-density urban areas, regardless of their size, are crucial factors affecting people's perception of green spaces and their mental health [25–29]. This highlights the significant impact of MUGS on people's behavior in green areas and their physical and mental health. Well-designed and strategically located MUGS in these high-density cities can provide enriching spatial experiences, strengthen the interaction between people and nature, and effectively meet the local residents' diverse recreational and social needs [30,31], thereby enhancing their sense of belonging, happiness, and overall health benefits [32–35]. Therefore, MUGS is considered one of the key green space types that promote outdoor activities in high-density urban areas and assist in the recovery and promotion of mental health [36,37].

### *1.2. Influences of Green Space Layout on People's Behavior and Health*

Previous studies have pointed out that green space functions [38,39], layout structure, vegetation coverage [40], and location [1] are significant factors influencing the frequency and duration of people's recreation in green spaces, types of activities, and the mental and physical health of people [41,42]. Higher green and water body coverage, a wealth of facilities, and the accessibility of various paths all contribute to fostering green space behaviors, enhancing social activities in green environments, and improving mental health [43–45]. Conversely, more hardscapes (sidewalks, structures, etc.) can produce negative effects [1]. Therefore, a well-planned layout of greenspaces should harmonize these different environmental elements to impact walking, resting, and other green exercises positively.

However, there are limited studies focused on the relationship between the layout of MUGS and people's behavior. A well-planned layout of MUGS could effectively enhance the connectivity between the green space and surrounding public and service facilities, increasing the usage of green spaces by the population [46,47]. Due to the differences in the spatial components and pedestrian distribution of various green spaces, the methods used in the study of the spatial layout of large parks could not be applicable to the study of MUGS [9,48].

It is notable that in the planning of high-density urban areas in China, a large number of MUGS are being designed to meet the green space needs of the population (Ministry of Housing and Urban-Rural Development of the People's Republic of China. Standard for Classification of Urban Green Space, 2017). Although massive MUGS have been constructed, the core issue of whether these spaces truly meet the behavioral needs of the public for green spaces remains unresolved. In the process of promoting the construction of MUGS in Chinese cities, problems such as difficulties in operation and maintenance, blind imitation, and an overemphasis on aesthetics over functionality have emerged [49,50]. Although previous research has explored planning and design strategies for creating MUGS that meet the activity needs of the population [51,52], these strategies are often obtained from field research on specific green spaces. The link between the layout of various spatial elements of the landscape and the distribution patterns of people's activities in green spaces has not been established, which is essential for the effective shaping and optimization of MUGS.

### *1.3. Layout and Crowd Activities in Mini Urban Green Spaces*

The development of digital techniques provides support to the simulation and studies of people's behavior and activities in urban green spaces. For instance, researchers use mobile signaling data or call records to track the distribution and flow changes of people within green spaces and apply these analyses for green space management and evaluation [53,54]. Some researchers have used the random forest algorithm to predict crowd movement patterns, but limitations related to the granularity of sample data, difficulty in data acquisition, and privacy concerns have restricted the widespread application of this prediction method [55]. Given the uniqueness of MUGS and the diversity of crowd behaviors within them, it is necessary to propose a crowd behavior simulation and evaluation model that is adaptable to MUGS.

In recent years, agent-based modeling techniques have been applied in the planning and management of large green spaces, natural scenic areas, and theme parks [56–58]. These studies typically focus on the effects of surrounding facilities, evacuation entrances, and other factors on tourist intensity, density, and crowd dispersal [59–62]. To consider the individualized needs of green-space usage, some scholars have attempted to discuss and simulate the distribution of attractions and the organization of pathways within green spaces using multi-agent systems, starting from the perspectives of tourist needs or the enhancement of social services provided by green spaces [63–66]. These studies have demonstrated that multi-agent simulation analyses have the potential to address issues related to MUGS layout and crowd activity but are currently not being fully explored in research.

Previous studies have often indicated a link between the behavior of individuals in MUGS and their spatial layout [67–70], but they have not clearly elucidated the specific interactions and key influencing factors between the two. Based on this, the aim of this study is to explore the relationship between the spatial layout of MUGS and crowd activities. The research questions include: (1) How can crowd behaviors in MUGS be simulated? (2) Do changes in the spatial layout within MUGS affect the distribution of crowd activities? (3) How can the spatial layout be adjusted to vary the potential distribution of crowd activities within MUGS?

To address these questions, this study selected a MUGS in Nanjing as the study area. After constructing a crowd activity simulation model based on field survey data, preliminary investigations were conducted on the AnyLogic platform by altering four variables: entrances/exits, pathways, node areas, and the number of facilities, to explore their impact on people's activity and distribution. Further, the key element affecting crowd activity characteristics (pathway) was selected for an in-depth exploration of its distribution characteristics and the correlated impacts on crowd behaviors. The innovation of this paper lies in the use of multi-agent simulation technology to establish the correlation between the behavior of individuals in green spaces and the spatial elements of mini green spaces,

and to identify the significant spatial factors that influence activities in these green areas. The results of this study, as well as the proposed analytical methodology, will potentially provide decision-making support for the future design, renewal, and management of MUGS. Meanwhile, the use of multi-agent simulation offers the possibility of designing MUGS incorporating crowd activities.

## 2. Methodology

### *2.1. Research Workflow*

To study the relationship between spatial layout and crowd activities in MUGS, this research has designed a workflow (Figure 1), which includes data collection, data processing, AnyLogic model construction, simulation and visualization, and result analysis. The research gathered spatial and crowd activity data through field surveys and drone photography. Then, we used the AnyLogic platform to construct models of the site and crowd activities. By altering the spatial layout elements of green spaces, the study simulated crowd interactions and distributions to explore the relationship between spatial layout and crowd activities.

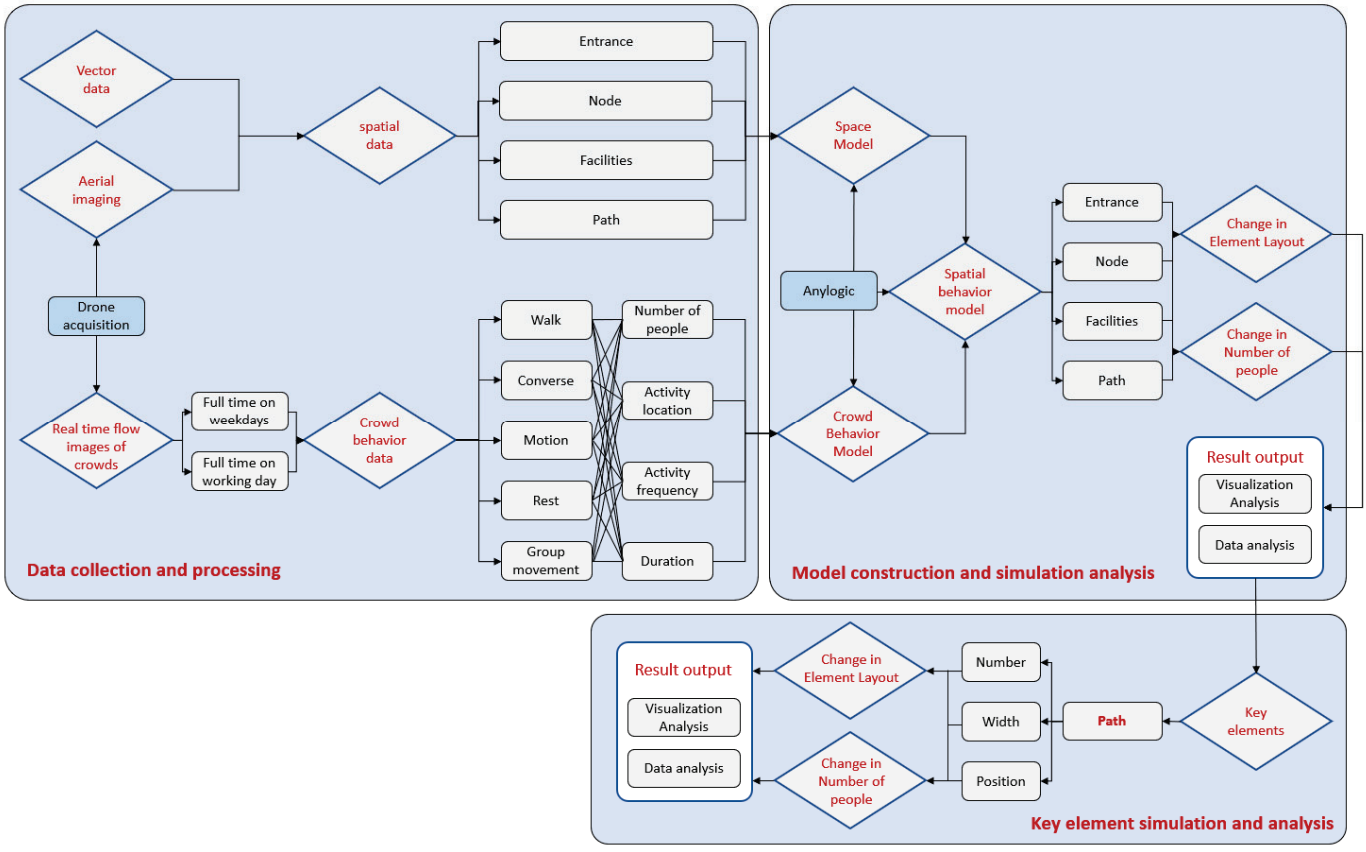



**Figure 1.** Research workflow.

### *2.2. Study Area*

This study selected one MUGS in Nanjing, China, as the study area. We began with a preliminary survey of MUGS within the main urban area of Nanjing using satellite imagery. Based on the local definition of the size of urban MUGS, 15 sites ranging from 0.5 ha to 1 ha were initially selected. Further field research was conducted on these selected green spaces. Considering factors such as the usage of the green spaces, function, layout, completeness of internal service facilities, and the types of surrounding land uses, Park 511 in the Qinhuai District of Nanjing was ultimately chosen as the research subject (Figure 2).

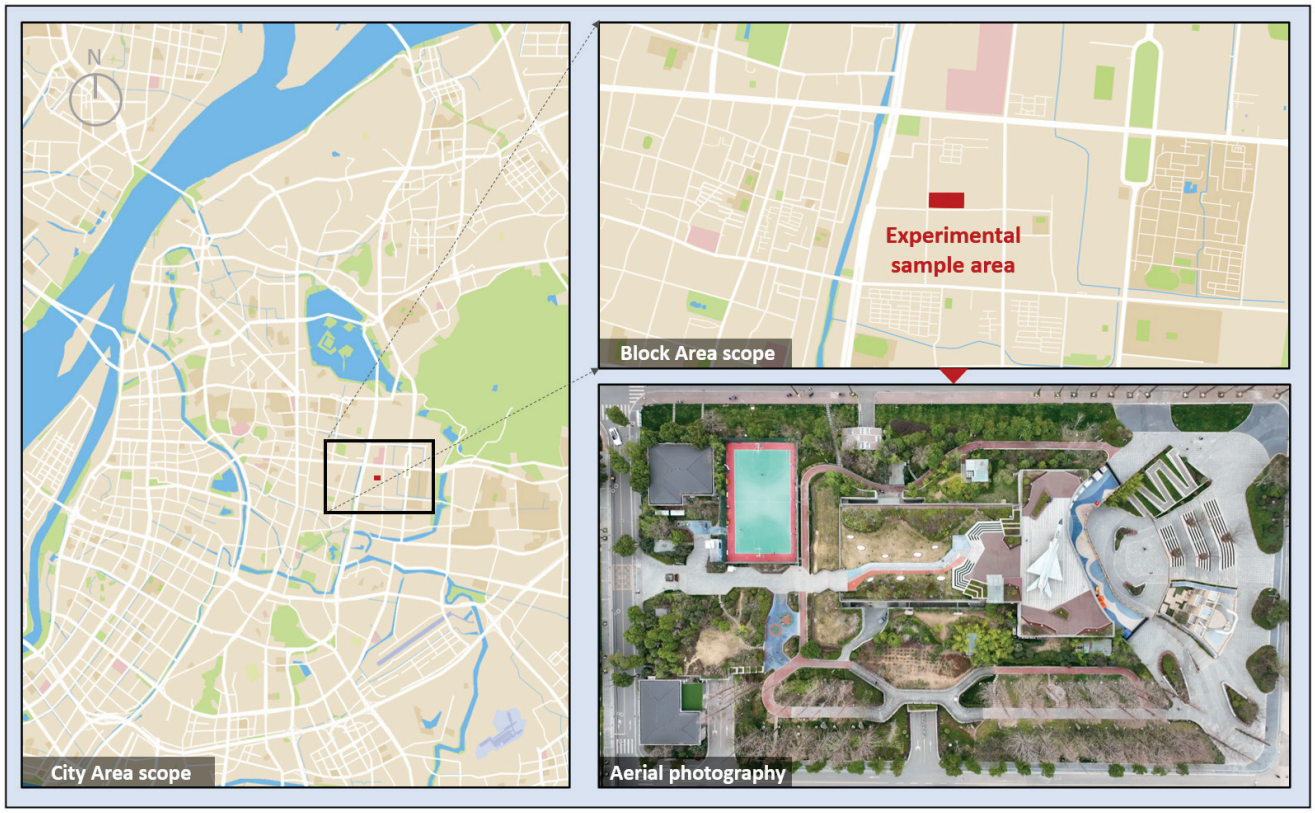



**Figure 2.** Study area.

The 511 Park was formerly the site of Factory 511, now situated at the heart of the factory area. It is a thematic park that integrates aviation culture with historical landscapes. Representing the main characteristics of mini green spaces in the Chinese region, the park covers an area of approximately 0.97 hectares. Surrounded by residential areas to the north and east, it is adjacent to a technology hub and sports center to the south and close to two commercial buildings and a major traffic artery to the west. About 400 m to the north is the Xi'anmen subway station, ensuring convenient transportation. The park is connected to surrounding roads through multiple entrances and exits and forms a green network within the Aviation Science and Technology City, linked with adjacent green spaces. The park boasts well-equipped facilities for recreation and exercise and high-quality plant landscapes. With low construction intensity and a tranquil environment, the park is primarily used by local residents. On weekdays in the evenings and during holidays, it also attracts visitors from other parts of Nanjing to experience its landscape. Overall, it has a high intensity of use. Internally, the site includes a basketball court, fitness equipment area, hard plaza, children's sandbox, and fitness trail, catering to the activity needs of different age groups with a high frequency of use.

### *2.3. Data Collection*

This study involved the collection of spatial data and crowd activity data from Park 511. The spatial data primarily consists of the park's site plan and the distribution of facilities within the area. Initially, CAD drawings were created based on satellite images of the site. Further differentiation of surface materials (soft and hard), as well as locations of entrances, seating, and exercise equipment, was achieved through field surveys. Lastly, the areas accessible to the public were clearly delineated, and the functions of various nodes were documented.

Unmanned Aerial Vehicle (UAV) digital photography technology allows for rapid and accurate gathering of information within a small area, covering aspects such as land use types [71], vegetation coverage [72,73], and crowd activities [74]. This study combines

UAV photography with on-site surveys to record spatial data and crowd activities in Park 511. In our study, we have deliberately chosen a method of data collection that does not capture specific individual attribute information, focusing solely on the activities of the crowd. This approach is distinct from mobile phone signal data, which often includes personal identifiers such as phone numbers, user names, ages, and other demographic details. To respect privacy concerns, we have abstracted the individuals within our research area into "action points", collecting only the behavioral patterns and spatial distribution characteristics of the active population. Our field surveys entail direct observation by researchers of the crowd's activities at the site during the photography period, supplemented by photographic evidence to assist in assessing and augmenting the statistical data on crowd dynamics. Researchers specifically selected nonrainy and other extreme weather conditions based on weather forecasts. During the survey period, the weather generally ranged from cloudy to sunny, which did not affect the various green-space activities of the people within the site.

To collect representative data on crowd activities, researchers conducted filming in clear, windless weather using a DJI Mavic 3 Pro drone to capture real-time video data of the research site. Filming times were set for the morning (8:00–8:15), late morning (10:00–10:15), midday (12:00–12:15), early afternoon (14:00–14:15), late afternoon (16:00–16:15), and evening (18:00–18:15). The drone was flown at an altitude of 340 m, allowing the camera to cover the entire park and adjacent roads, clearly distinguishing various spatial elements, vegetation, pets, and types and states of crowd activities within the park. Additionally, types of crowd behavior in the park, such as walking, running, basketball, chatting, dog walking, sightseeing, exercising, hanging out, resting, childcare, playing, and using restrooms, were recorded through observation.

We collected the data on 8 March, 11 March, 20 March, 2 April, 1 December, 3 December, 15 December, and 17 December 2023, covering four weekdays and four weekends, totaling eight days of video data. Nanjing experiences spring in March and April, and late autumn in early December. During these periods, the climate in Nanjing is mild and suitable for outdoor activities. Springtime, the season for enjoying the greenery, sees an increase in visitors to parks in Nanjing who engage in social activities. This provides a substantial volume of data for the study. Moreover, during both spring and late autumn, the shading effect of deciduous trees in the park is significantly reduced, which helps to decrease data errors in subsequent statistical steps for crowd activity.

### *2.4. Data Processing*

In terms of crowd activity data, due to the individual variability in crowd behavior, there is a vast array of crowd subcategories within MUGS. We have selected the most representative activity types with the highest number of participants. By combining current status surveys and aerial photography data, this study categorizes the main crowd activities in the park into five types: walking, resting, group sports, conversing, and exercising (Figure 3). Each activity type is analyzed in terms of location, setting, rate, duration, and number of participants. The aerial imagery data samples from various time periods underwent frame extraction (15 s per frame), resulting in 2880 frame segments, which adequately cover variations in crowd activities during these times. Using manual counting, the number of people engaged in each activity type, the walking speed of the crowd, the duration of activities, the number of facilities at each node, and the crowd flow at entrances and exits were quantified from the frame data.

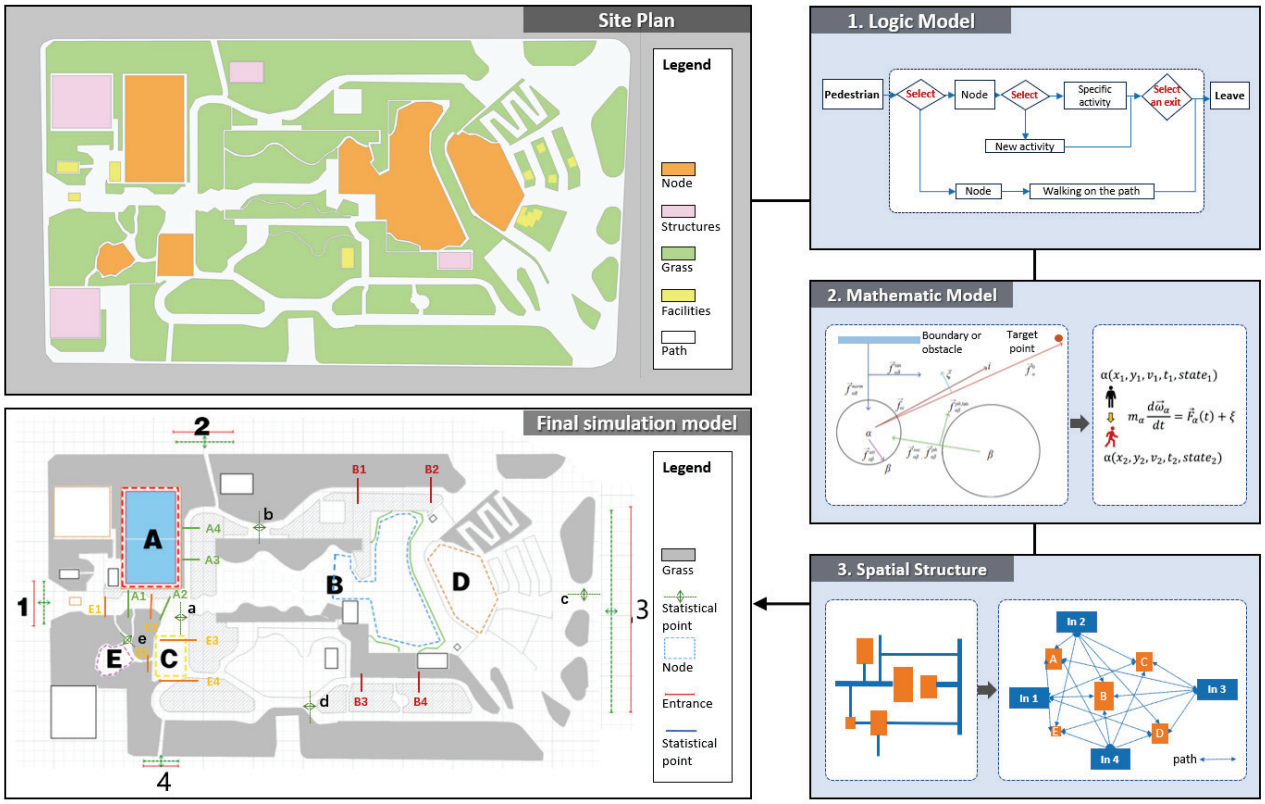



**Figure 3.** Site modeling logic and final modeling scenarios.

### *2.5. Construction of the Spatial Behavior Model*

This study utilizes the AnyLogic platform to model the space and crowd activities of Park 511. As a pedestrian simulation software, AnyLogic has been widely used in simulating landscape space crowd activities and studying the correlation between crowd behavior and the environment [75–79]. Spatial data were imported into the AnyLogic software for transformation, primarily defining and clarifying the overall spatial layout, functions and areas of various nodes, and conditions of site facilities, pathways, and entrances. These definitions helped form corresponding spatial modules. Elements from the software's Pedestrian Library were used to represent impassable features such as planted lawns, landmarks, and fences as "Wall" modules. Markup tools delineated nodes to define the boundaries of crowd activities, with four entrance and exit locations and attributes set using "Attractors" to represent service facilities placed in nodes and pathway modules.

In terms of crowd behavior logic, to more accurately simulate various activities, specific behavioral processes were established for five types of crowd activity. Based on behavior observations and data processed from the tables, appropriate movement rules and speeds were set for different types of activities. According to crowd activity data obtained from a field survey (Figure 4), it was observed that walking and conversing were distributed across various nodes, and both group sports and conversations tended to form teams. Resting and exercising depended on the distribution of facilities within the site, such as benches and fitness equipment. Additionally, there was a significant amount of walking and crossing behavior on fitness trails and entrance plazas. Whether inside nodes or on plazas, walking behavior was random, whereas crossing behavior was purposeful and directional. The study defined the behavior of crowds entering nodes or pathways from entrances as driven by self-propelling forces, pedestrian interaction forces, and environmental resistance. The self-propelling force was directed towards the target node or pathway, pedestrian interaction forces were defined by the underlying social force model of the software dictating interactions among individuals, and environmental resistance related to the layout of surrounding "walls," i.e., the spatial model (Figure 3).

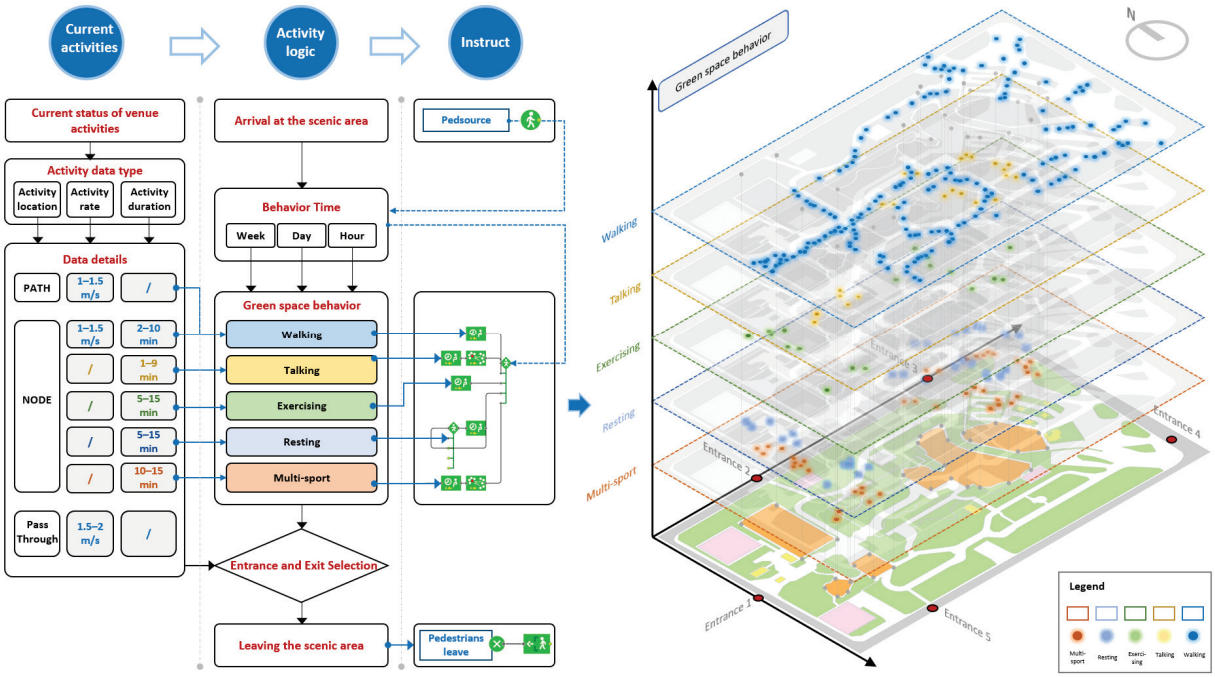



**Figure 4.** Crowd activity modeling logic and corresponding usage modules.

Therefore, within the model, once pedestrians enter a node, they engage in activities according to observed patterns (searching for resting or exercising facilities to engage in activities, forming teams for group sports or conversational activities, or undertaking random walking movements within the node). Based on field research findings and different pedestrian element modules in the analytical platform, the study built a logic diagram of crowd behavior internal to the research area, completing the setup for crowd movement (Figure 4).

Further research has found that the type of activities and the number of people engaging in activities vary across different nodes, and the flow of people through various entrances and exits differs significantly. It is necessary to calculate the probability of occurrence of various activities in each node and the probability of people choosing different entrances and exits. Based on statistical data obtained from the data processing section, this study inputs parameters for various activities into the crowd behavior logic diagram, sets attributes and the flow of people for each node and entrance/exit, and links the spatial model with the modules of crowd behavior logic. With the help of the pedestrian library in the software, the model's runtime and speed are set to simulate the behavior of the park's crowd. During the simulation run phase, real-time monitoring of the quantified results of various activities is conducted through the AnyLogic panel, and visualization of the people flow results for specific time periods is output via a time-series graph according to analytical needs. The results from the simulation experiments indicate that the simulated people flow, trajectories of crowd movement, types of activity, and timing of crowd activities closely match the actual field research conditions of the park, providing an accurate simulation of the behaviors and states of the park's crowd.

### *2.6. A Two-Step Crowd Activity Simulation and Analysis Method*

To explore the relationship between the layout of various spatial components and people's behavior and distribution in MUGS, we developed a two-step approach. First, we selected four spatial components of MUGS as variables, including entrances, pathways, nodes, and facilities. After altering these four types of spatial elements, based on the already constructed crowd activity model, we analyzed the overall situation of people flow distribution in the MUGS. In terms of entrances, there is one main entrance on each of the east and west sides of the park and one secondary entrance on each of the north and south sides. Following the

principle of consistency in entrance rankings on the same side, additional entrances were added sequentially in all four directions of the park, connecting the new entrances to the existing pathways and resulting in five different configurations of entrance numbers and locations. Regarding pathways, the study increased the paths between nodes and between nodes and main roads, setting up five different pathway layout patterns. The area of nodes and the number of facilities were increased proportionally based on their original attributes, simulating increases from 10% to 50% in five scenarios (Figure 5).

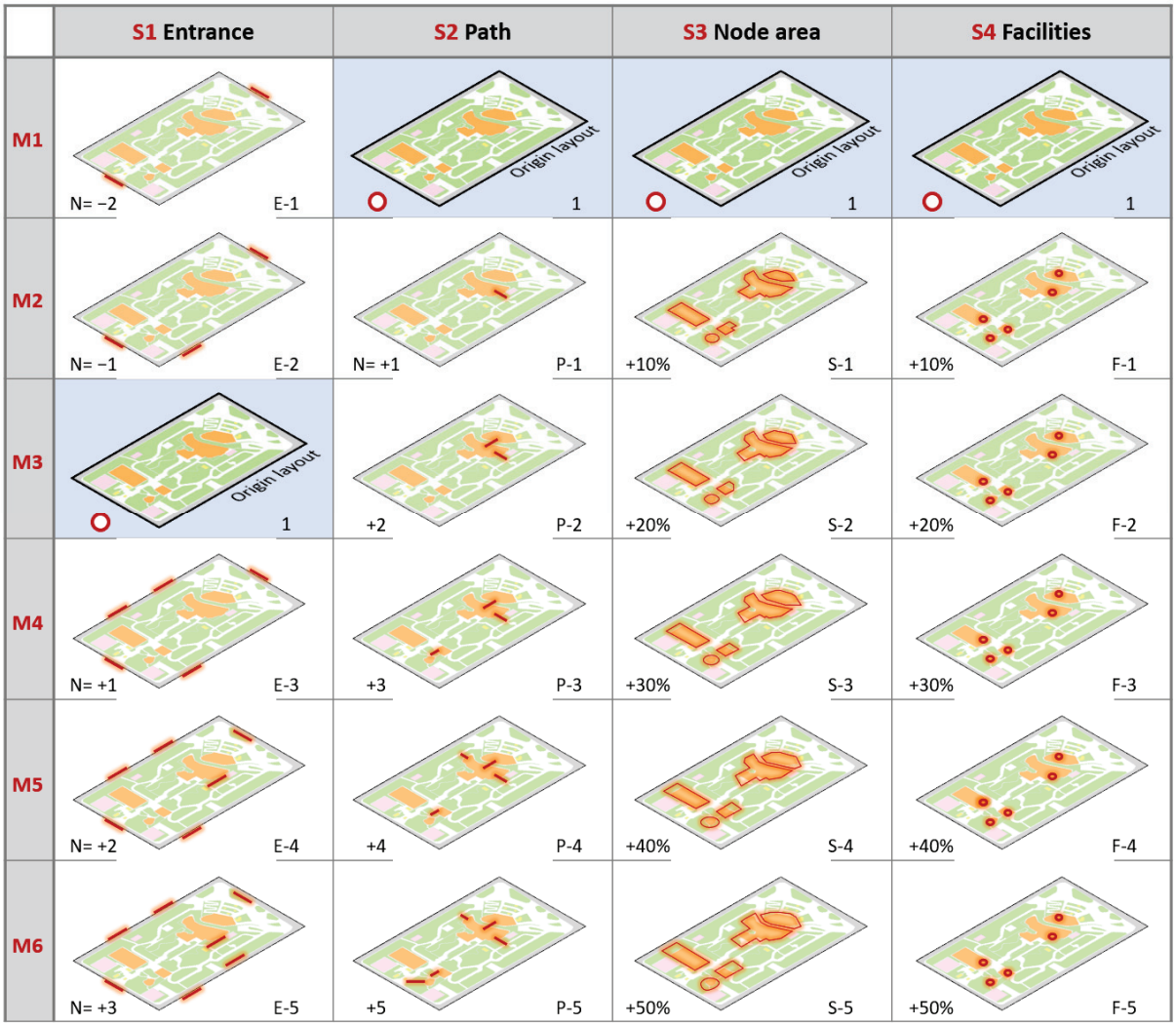



**Figure 5.** Site classification mockups.

To characterize the overall crowd activity and distribution within the park, this study set up pedestrian flow monitoring points both inside various nodes and along the main loop of the park. These monitoring points (lines) are uniformly distributed in areas where pedestrian traffic and activities are concentrated (Figure 3). Once the crowd activities in the model stabilized, the simulation continued to run for one hour. During this time, the total and peak numbers of people within each node, as well as those passing near the monitoring points, were collected in real-time. The peak pedestrian density near each monitoring point was calculated based on the traffic recorded five minutes prior to each specified time point. The peak and total numbers of people at each point (cross-section of the pedestrian flow line) were then tallied. It should be noted that with each simulation, the number of people entering the park in AnyLogic fluctuated by approximately 5–10 individuals; hence, results for smaller crowds could vary by a margin of 3–5 people. To minimize significant errors in simulation outcomes, this study averaged results over multiple simulations.

Following the comprehensive analysis outlined above, the study identified factors that significantly influence pedestrian distribution. Focusing on individual nodes within mini green spaces, the study conducted multiple simulation experiments by altering spatial element layouts (such as position and quantity) around or within the nodes to explore further the relationship between these factors and crowd activity characteristics.

### *2.7. Statistical Analysis*

The study set up a series of pedestrian monitoring points and used the number of people passing these points per unit of time to comprehensively describe the crowd activity characteristics in the green space (Figure 3). Specifically, the study documented the flow of people within each node and near the monitoring points, as shown in Figure 6, with the peak traffic near the monitoring points expressed as X persons per hour. (From the default simulation perspective, when the software simulation reaches approximately five times the original flow of people (7250 people/day), there will be minimal change in crowd activity. Our simulation settings are based on the original and twice the original flow of people, and no congestion was observed at any node during the simulation process).

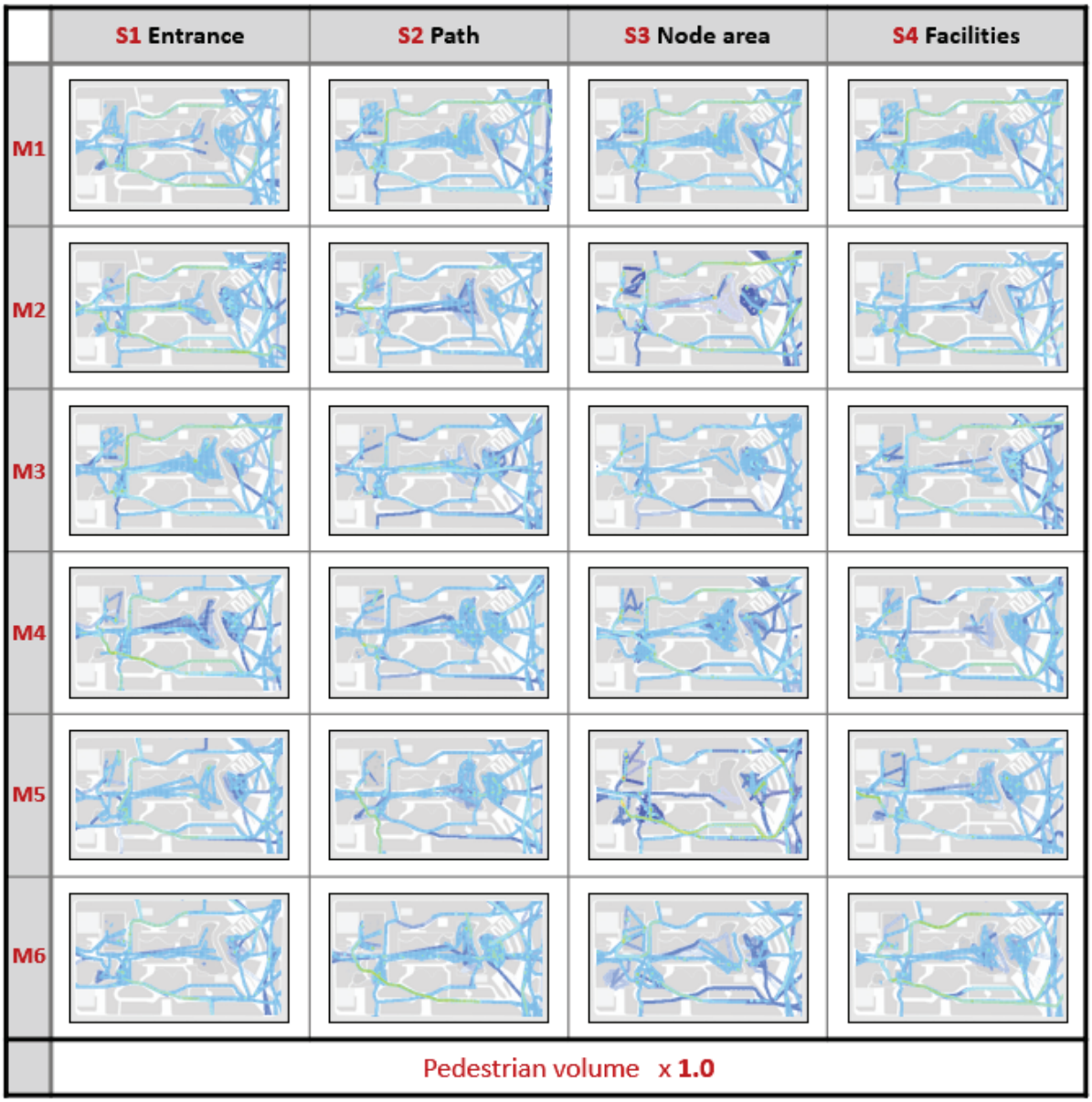



**Figure 6.** Impact of changes in the layout of the four spatial elements on pedestrian activity.

## 3. Results

### *3.1. Results of the Current Pedestrian Flow Model*

Figure 7 illustrates the simulation results of the original green space. No congestion occurred at any node. Notably, Node D had the highest peak with seven people, which corresponds with the actual heavy foot traffic observed at this location. In contrast, Node E experienced the lowest peak with only one person. Considering the total number of people within the nodes, the average was 21 individuals. Nodes A and B had similar counts, approximately 18 people each, slightly below the average, while Node C's total was slightly above the average. These figures align well with actual observations. The total number of people in Node D was significantly higher than in other nodes, with 26 people engaged in activities and 22 merely passing through Node D. Nodes A, B, C, and E each have only one path connecting them to the main road; thus, all individuals entering or exiting these nodes were involved in activities, with no through traffic. This means the simulation data accurately reflected the number of people active within the nodes.

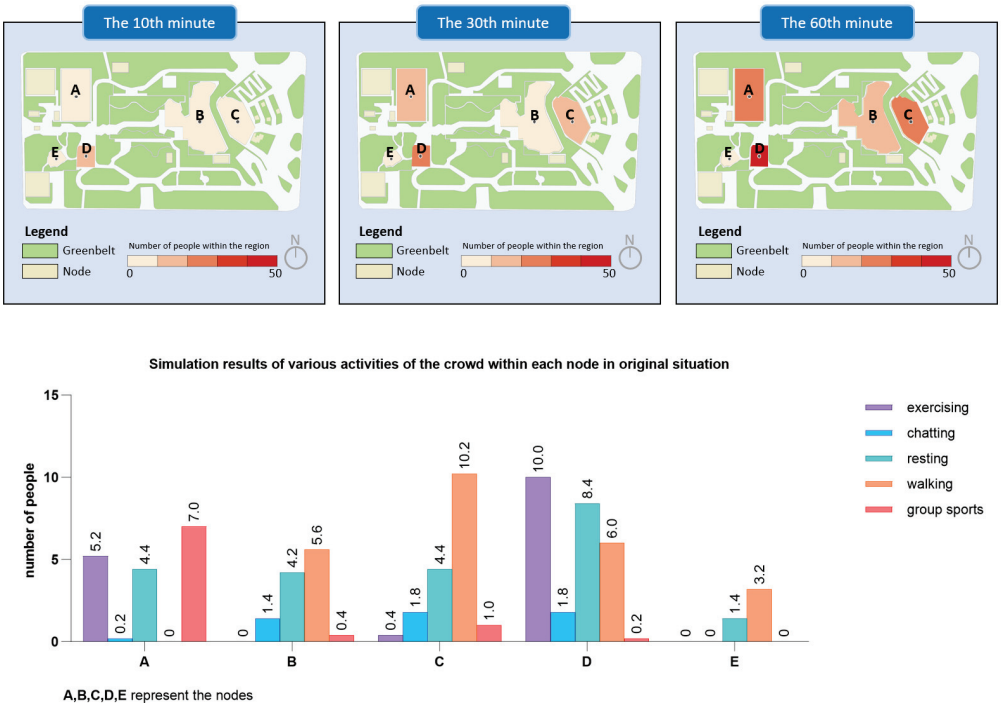



**Figure 7.** Status quo crowd modeling results.

From the monitoring point data, the peak pedestrian flows near points a, b, d, and e were quite similar, all around 80 people per hour, indicating a generally low density of crossing traffic. However, point c exhibited the highest peak at 120 people per hour. Field observations confirmed that point c was near a large number of people, both crossing and walking, which also tends to be denser, aligning with the results. The total number of people passing near these monitoring points generally mirrored the trends in peak flows; points a, b, and e all saw around 25 individuals, while crowd activities were concentrated near points c and d, with point c seeing 58 individuals.

In terms of types of crowd activities, Node A has a high proportion of rest and exercise behaviors, while Nodes B and C are predominantly frequented by walkers, with a few people engaging in physical activities such as exercise. Specifically, at Node C, the number of walkers reaches 10. Node D is equipped with a variety of fitness facilities and thus has the highest number of people engaging in exercise activities, totaling 10 individuals. In Node E, there are almost exclusively people walking and resting, with the number of individuals in both activities being less than four.

The consistency between the simulated situations and the collected statistical data shows that the simulation closely replicates actual conditions and can quantitatively explain the distribution of crowd activities in MUGS.

### *3.2. The Relationship between Four Spatial Layout Elements and Pedestrian Distribution*

This study examined how changes in entrances, pathways, node areas, and facilities affect pedestrian distribution by modifying the spatial model and using the current pedestrian flow model as a basis to explore the relationship between crowd activity characteristics and spatial layout. The total number of people at each node and monitoring point after the simulation is shown in Figure 8. Additionally, we have also output the quantity of five types of crowd activity at each node under four variable patterns. The simulation data indicates that the four elements have varying impacts on the overall number of people, with changes to pathways and entrances exerting a more significant influence on pedestrian distribution.

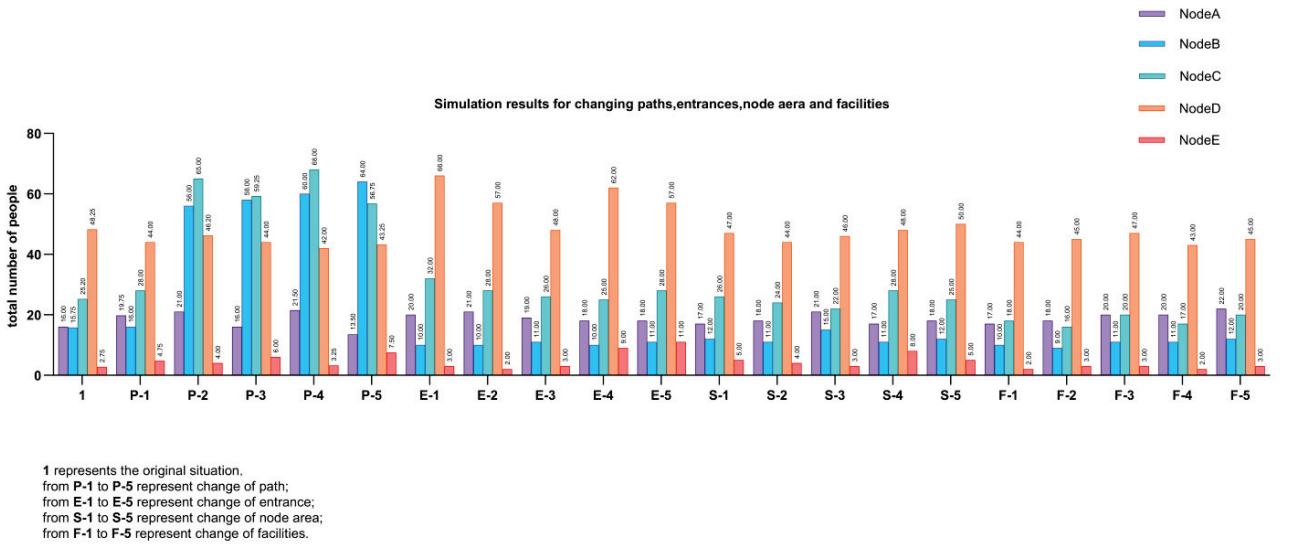
#### 3.2.1. Entrances

When the number of entrances changes, there is generally a minor variation in the peak pedestrian flow near nodes and monitoring points, with a consistent trend in changes. In terms of total numbers, the trend in total people at each node remains the same, with only slight variations at individual nodes. The overall change in total numbers at each monitoring point is small, with significant variations at individual nodes. Specifically, the total number of people inside nodes A, B, and C varies little, not exceeding five people. Node E, under the E-5 scenario, shows a substantial increase of seven people, a change exceeding 200 percent. Node D, when the number of entrances increases from five to six, sees an increase from 48 to 62, a growth of 30 percent. The total number near the monitoring points shows a clear categorization: numbers are one category when entrances are fewer than four, and another when there are four or more, with minor differences of less than eight people within the same category. The main differences between the two categories are evident near monitoring point b, with variations ranging from 16 to 24 people. From the distribution of various crowd activities, the types and quantities of crowd activities at each node are similar to the original conditions.

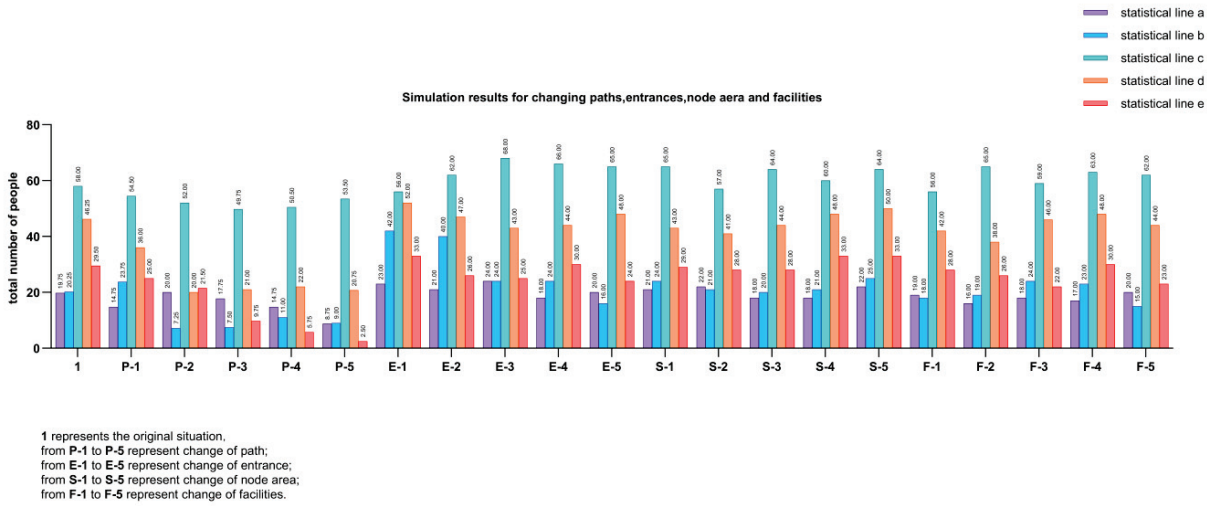
#### 3.2.2. Paths

When the number of pathways within the park changes, it significantly impacts both the pedestrian flow near monitoring points and the total number of people within nodes. For instance, Node B under scenario P-5 has the highest count at 64 individuals. The total counts in nodes A, D, and E across various scenarios (P-1 to P-5) show small differences, with the maximum difference in nodes A and E not exceeding seven and four people, respectively. Nodes B and C display substantial variations in total numbers under different scenarios. For example, after adding a fifth pathway (P-5), the pedestrian count at Node B is 64, a difference of 48 from the original count of 16, marking a 300% increase. In contrast, Node C shows little variation between the original and P-1 scenarios, differing by only 3 people, with an average of 26.5. From scenarios P-2 to P-5, the average count is 61, exceeding a 100% increase, and the numbers between these scenarios vary little. The trends in peak and total numbers near pathway points are consistent.

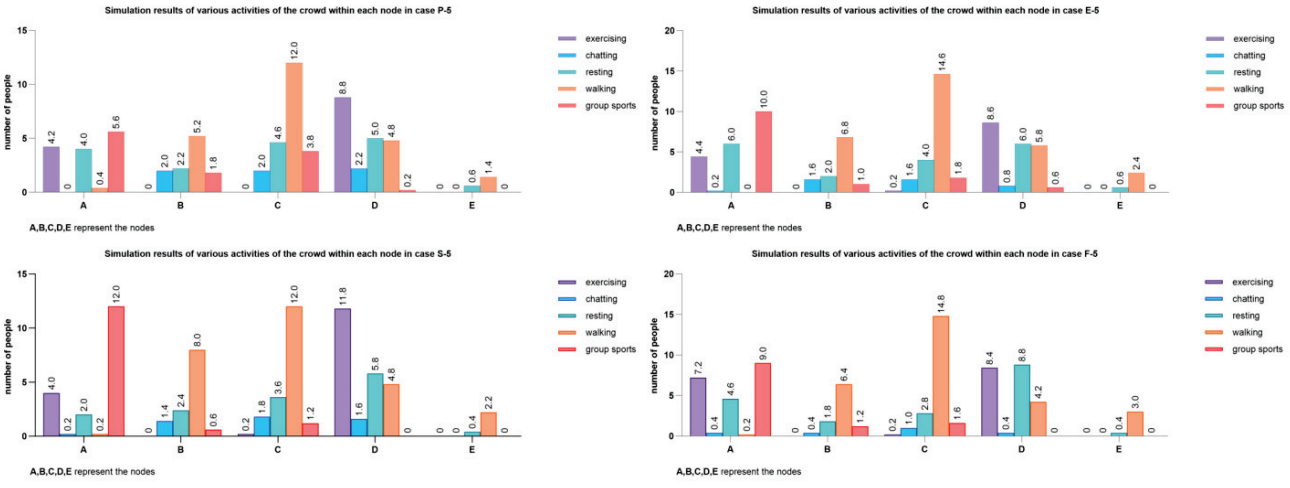
In terms of total numbers near the monitoring points, point c still records the highest figures, originally reaching 58 individuals. Points a, b, d, and e all experience significant changes under various scenarios, with points d and e showing the most noticeable changes. The differences between scenario P-5 and the original scenario (1) are 26 and 27 people for d and e, respectively. The total count near point e decreases with the addition of pathways and shows clustering.




(**a**)




(**b**)




(**c**)

**Figure 8.** Changes in the layout of spatial elements and changes in the pattern of change of human flow activities: (**a**) Simulation results of nodes; (**b**) Simulation results of statistical lines; (**c**) Simulation results of various activities of the crowd within each node.

It is noteworthy that changes in total numbers at nodes under different scenarios show similarities. For example, the original scenario (1) and P-1 form one group, while P-2 to P-5 form another, with little intra-group variation and larger inter-group differences. Regarding monitoring point data, the trends in peak and total numbers are consistent, and changes in peaks reflect those in total numbers to some extent. Upon examining the distribution of various crowd activities, it is observed that the number of people engaging in group sports at Node C has increased by three individuals, while the crowd activity at other nodes remains relatively similar to the original conditions.

#### 3.2.3. Node Area

When the area of park nodes is proportionally increased, changes in both the total number of people within nodes and the pedestrian traffic at monitoring points are minor. Specifically, the maximum count within nodes is 50 people at Node D under scenario S-5, a difference of only two people from the original scenario (1). The differences among nodes A, B, and C are small and consistent with actual conditions, with the total count variations across scenarios (S-1 to S-5) not exceeding 20%, which is very close to the original scenario (1). The largest change in monitoring point counts between scenarios S-1 to S-5 and the original scenario (1) does not exceed 15%.

In terms of the distribution of crowd activities, when the area of the nodes was increased by fifty per cent, the number of people participating in group sports at Node A rose by five individuals.

#### 3.2.4. Facilities

When the number of facilities within the park increases proportionally, the resulting changes in pedestrian traffic at nodes and monitoring points are similar to those observed with area changes. Specifically, the largest difference in total numbers across nodes in scenarios F-1 to F-5 is only five people, occurring between scenarios F-1 and F-5 at Node A. The differences in total numbers near each monitoring point in various scenarios do not exceed 10 people. The total count changes at both nodes and monitoring points across scenarios F-1 to F-5 do not exceed 20%. From the distribution of crowd activities, it can be observed that when the number of facilities was increased by fifty percent, there were no significant changes in the types and quantities of crowd activities at any of the nodes.

### *3.3. Results of Pathway Changes around a Single Node*

To further investigate the impact of pathways on the distribution of crowd activities, this study focused on the element of pathways. By altering the number, orientation, and width of pathways connected to nodes, the study examined the variations in pedestrian flow within individual nodes and across the MUGS as a whole. Changes were made to the number and orientation of pathways around nodes A, B, and E. Specifically, fifteen scenarios (B-1 to B-15) around Node B were evenly divided into five groups (B-1 to B-3, B-4 to B-6, B-7 to B-9, B-10 to B-12, B-13 to B-15); eight scenarios each around nodes A and E (A-1 to A-8, E-1 to E-8) were divided into four groups (A-1 to A-2, A-3 to A-4, A-5 to A-6, A-7 to A-8; E-1 to E-2, E-3 to E-4, E-5 to E-6, E-7 to E-8), with changes in the number of pathways on the same side within groups and different orientations between groups. Due to a lack of space to add 6-m-wide roads around nodes C, D, and E, nodes A and B were selected for changes in pathway width, creating twelve different scenarios. The final pathway layout changes are illustrated in Figure 9. After simulation (Figure 10), the results shown in Figures 11 and 12 were obtained. It is noteworthy that the orientation of pathways has a significant impact on the distribution of pedestrian flow, whereas the number and width of pathways have minimal effects.

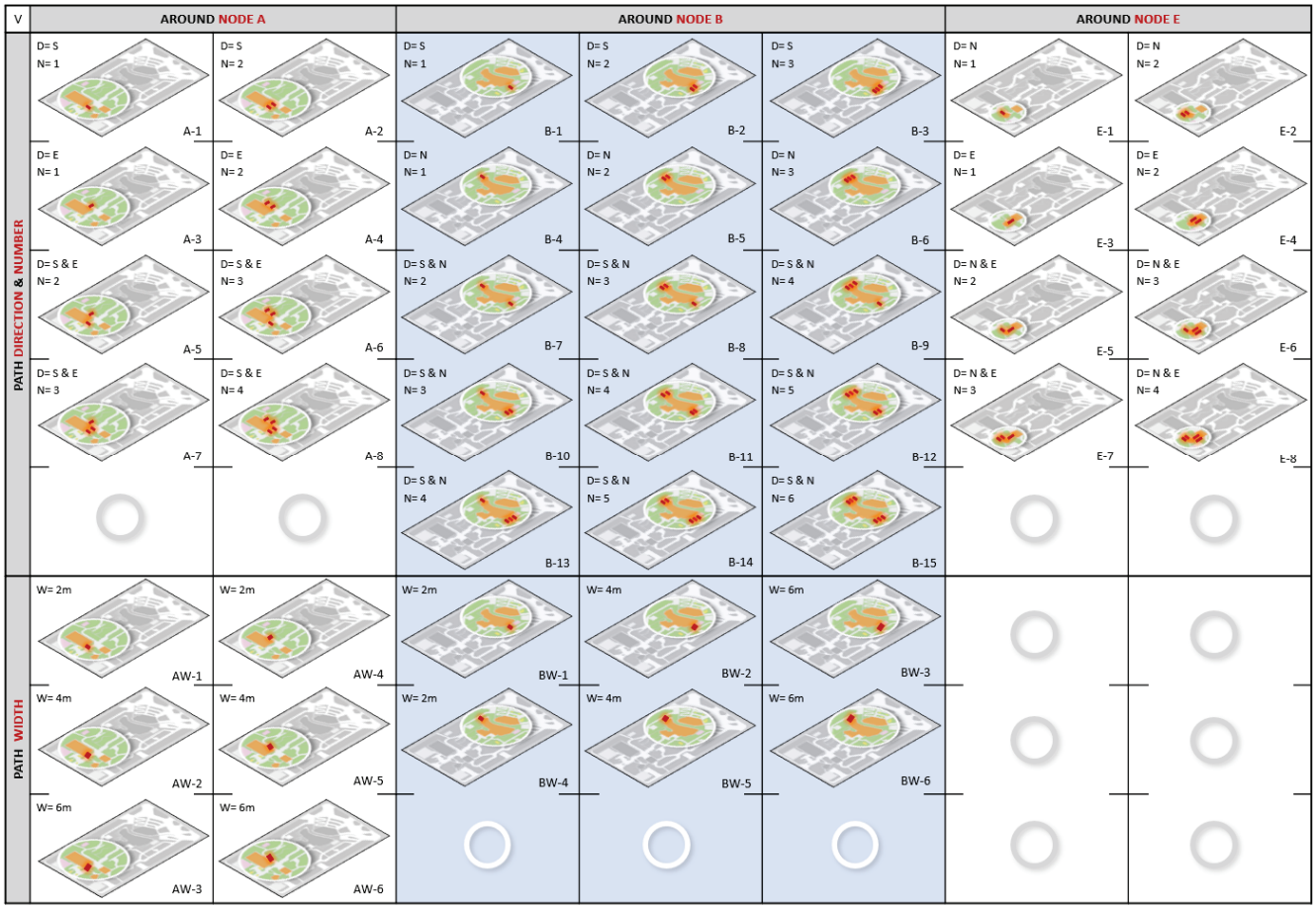



**Figure 9.** Node-specific—path change simulation (orientation, number, width) schematic.

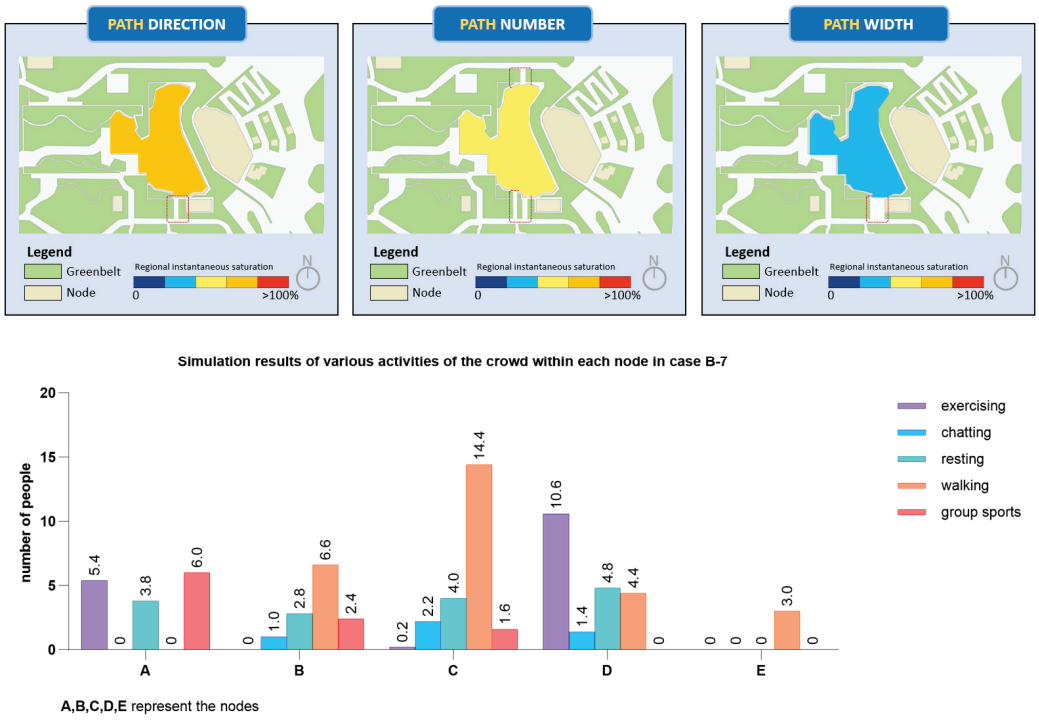



**Figure 10.** Visualization results of people flow changes in different path layouts—An example of node B.

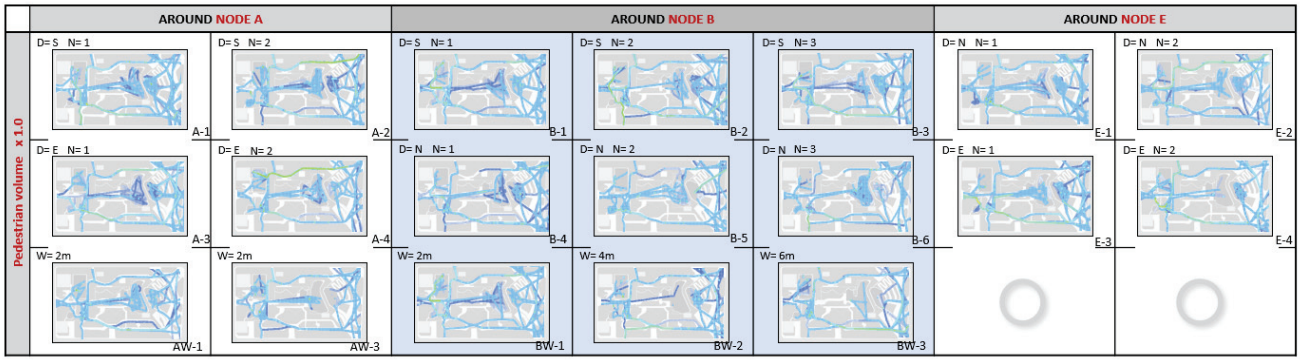
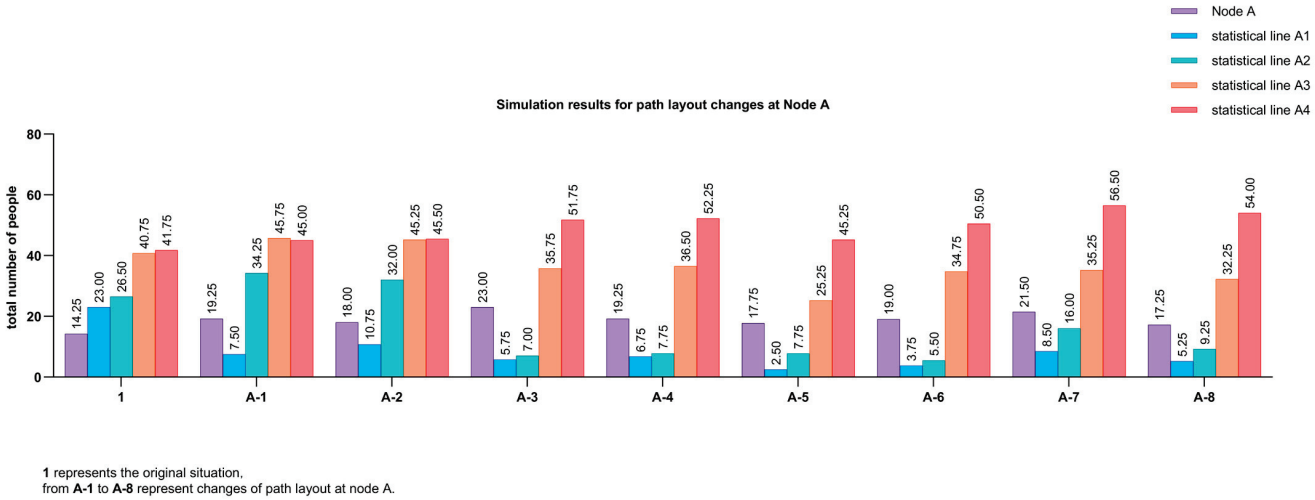
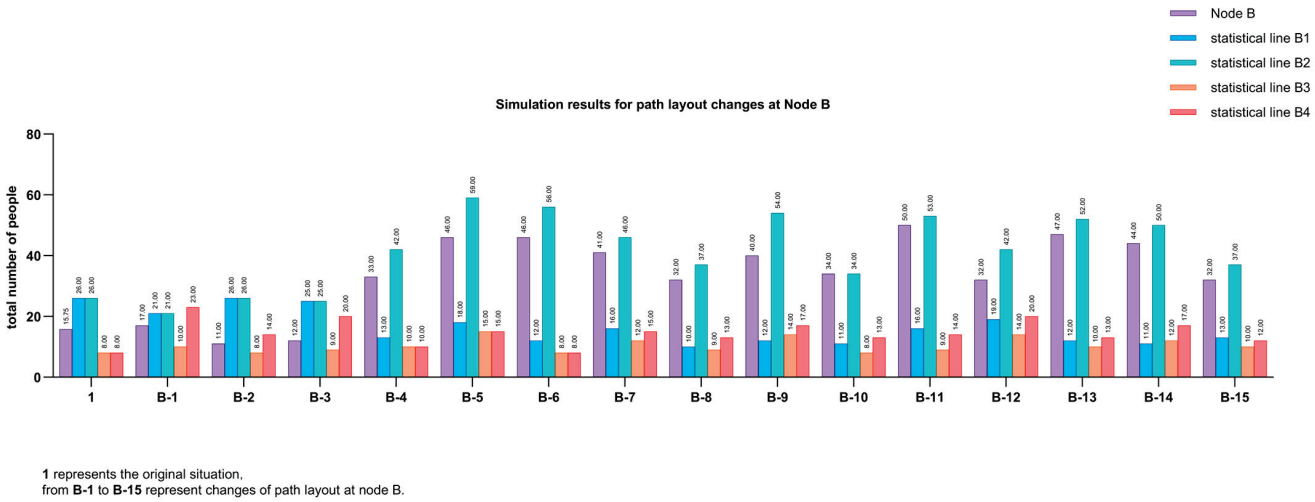



**Figure 11.** Impact of changes in spatial characteristics of paths on pedestrian activity.




(**a**)




(**b**)

**Figure 12.** *Cont.*

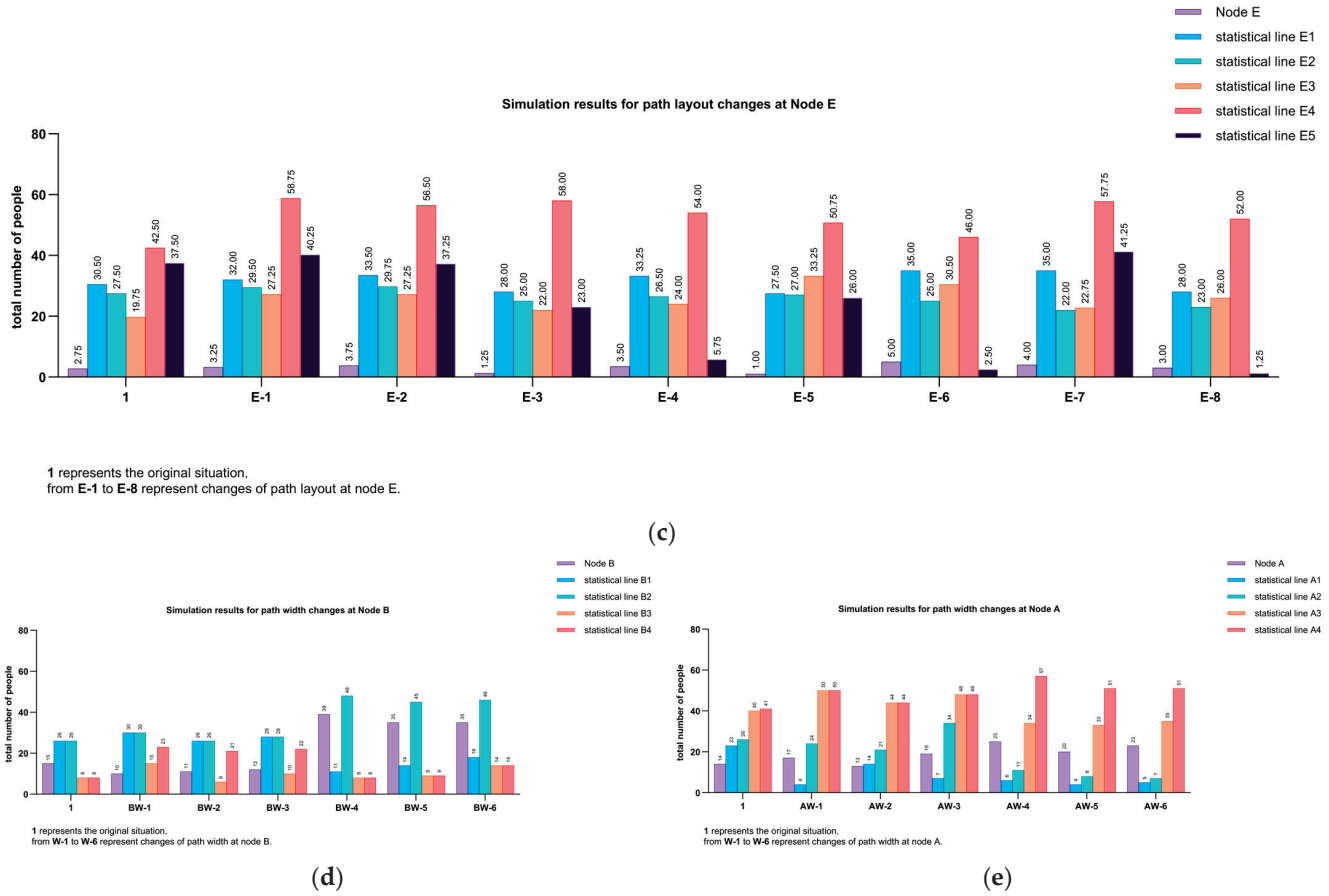



**Figure 12.** Changes in spatial characteristics of paths and patterns of change in pedestrian activities: (**a**) Simulation results for path layout changes at Node A; (**b**) Simulation results for path layout changes at Node B; (**c**) Simulation results for path layout changes at Node E; (**d**) Simulation results for path width changes at Node B; (**e**) Simulation results for path width changes at Node A.

This study compares the total number of people within the respective nodes and the total number of people passing through the pathways around these nodes.

### 3.3.1. Changing Path Orientation

When adding paths in different orientations, both the total number of people within the corresponding nodes and the total number of people on paths around the nodes undergo significant changes. When the orientation of paths around node B changes, the total number of people within the node varies greatly under different circumstances. For instance, there is a significant difference between the first group of results and the subsequent four groups, with a variation of 35 people between B-2 and B-5, representing a change of three hundred percent.

When the paths around node A change, there are relatively small differences in the flow of people within and between groups of node A. There is a significant variation in the flow of people on the surrounding paths, with noticeable differences between the first group (A-1 to A-2) and the subsequent three groups (A-3 to A-8). Upon comparing specific values, it is observed that the differences in the total number of people within each group of node A do not exceed five people, and the maximum difference between groups is five people, with a variation of no more than thirty percent. The differences in the total number of people on paths around node A are significant, showing distinct categorization between the first group and the subsequent three groups. The path points with significant fluctuations in values are A2 and A3. When the orientation of paths around node A changes (A-1 and A-3), the values of A2 and A3 rapidly decrease from 34 and 46 to 7 and 36, respectively,

representing changes of eighty percent and twenty percent, respectively. The value of A4 increases from 45 to 52, representing a change of fifteen percent.

When the paths around node E change, the intergroup differences in the total number of people within node E do not exceed thirteen percent, while there are noticeable changes in the total number of people on paths around the node. There are significant changes in the values of groups one and three at point E5. Comparing E-2 with E-4, the value at E5 decreases from 37 to 6, representing a change of over eighty percent.

Based on the intergroup data of nodes A, D, and E, it can be observed that the orientation of paths can have a certain impact on the flow of people within park nodes and a greater impact on the distribution of people around the nodes (local areas of the park).

#### 3.3.2. Changing Path Quantity

By comparing the values within groups of nodes A, B, and E, the distribution of people flows when the number of paths changes can be analyzed. As the number of paths within node groups increases, the differences in the total number of people within node B under fifteen scenarios of path changes (five groups) are relatively small, with a maximum variation of forty percent. When paths around nodes A and E change, the variations in the total number of people within the respective nodes and the surrounding path points are relatively small, showing a high degree of consistency in the data trend.

#### 3.3.3. Changing Path Width

This study conducted statistical analysis on six path scenarios for nodes A and B, categorizing each node's six paths into two groups (AW-1 to AW-3 and AW-4 to AW-6; BW-1 to BW-3 and BW-4 to BW-6) based on path orientation. The widths of paths within each group are 2 m, 4 m, and 6 m, respectively. From specific numerical observations, the differences in the total number of people within all scenarios at each node do not exceed three people, and the variations in the values of affected nodes and surrounding paths do not exceed thirty percent.

## 4. Discussion

### *4.1. Relationship between Spatial Layout and People's Distribution*

Previous studies have indicated a correlation between different human activities, mobility, and park layout elements [3,63,80–82]. Factors such as park accessibility, entrances and exits, paths, and facilities layout, attractiveness, and quantity are known to influence the intensity and distribution of green space activities. Similarly, in simulations of human behavior and crowd evacuation in other urban spaces, spatial layout [83], path structure [84], etc., are identified as crucial factors affecting human activities. These findings align with the results of this study on the simulation of human activities in MUGS. However, previous related research has not delved into the dynamic effects of significant influencing factors such as paths under variations in attributes like width, length, orientation, and quantity on human activities.

This study's simulation analysis of four types of spatial elements—paths, facilities, nodes, and entrances/exits—demonstrates that all these elements have a certain impact on the distribution of human activities in MUGS. However, park path layout emerges as the most significant influencing factor. The quantity and layout of entrances/exits also influence the distribution of pedestrians and activities. Conversely, changes in the area of mini green space nodes and the number of facilities have a relatively minor impact on human green space activities.

Specific simulation data comparisons reveal significant changes in the total number of people within nodes as path layout changes. When paths increase to one or more (P-1 to P-5), node B becomes a node with traffic properties as it connects with the main paths within the park. Although the number of people engaging in activities within node B remains unchanged, the increase in the number of people passing through node B to other nodes and paths leads to an increase in the total number of people within node B. When

paths increase to two or more (P-2 to P-5), node C becomes connected to node B, linking the two main entrances/exits and activity areas of the park. In essence, the significant impact of path changes on human activities is mainly attributed to altering the overall flow dynamics of the park, particularly as additional local paths modify accessibility to roads and nodes, resulting in systemic changes in the types and intensity of green space activities in different nodes. Previous studies utilizing spatial syntax analysis have also suggested that path changes affect green space traffic distribution [85–88].

Furthermore, when changing entrances/exits, the number of people passing through point b increases sequentially in scenarios E-2 and E-3. This is because, compared to the original scenario, in E-1 and E-2, the flow of people near point b is redistributed to other entrances/exits (passing through point b). It is noteworthy that although simulation results suggest that area and facilities have a minor impact on green space human activities, studies on green spaces in densely populated cities [89,90] have identified these as important influencing factors. This study speculates that this may be because, for MUGS, the number of users is far lower than that of larger parks in urban areas. Taking the example of the 511 Park studied in this paper, under normal circumstances, the nodes are not crowded, and existing facilities are sufficient to meet the needs of users. Therefore, increasing node area or facilities in this study may result in lower attractiveness for human activities.

### *4.2. Relationship between Path and People's Distribution*

Upon recognizing paths as pivotal influencers shaping both the activities and flow distribution of individuals within MUGS, it becomes imperative to delve further into how alterations in path spatial attributes directly impact green-space activities. Through a classification simulation study exploring diverse spatial changes in width, quantity, and orientation of paths surrounding key nodes within MUGS, it was discerned that path orientation emerges as a critical determinant affecting the flow dynamics and spatial distribution of individuals around these nodes.

From the research findings, the simulation data across the three path widths exhibit a high degree of consistency. Variations in green space activities and pedestrian flow are primarily observed in scenarios involving changes in the number of paths and their orientation. Taking this study as an example, altering the number of paths on the same side of Node B does not significantly affect the distribution of pedestrian flow within the node and its surrounding area. When new directional connections are established at Nodes A and E, the total number of people within these nodes does not change noticeably. However, when a new path is added to one side of Node B, there is a significant change in the pedestrian flow around Node B. Comparing the fifteen path layout patterns of Node B (B-1 to B-15) reveals that, as the number of paths on the south side of Node B increases from zero, the pedestrian flow near the north side count point B1 decreases, while the flow near the same side B2 significantly increases. The newly added paths have a clear regulatory effect on the distribution of pedestrian flow around Node B. This phenomenon occurs because Node B is centrally located within the park; when the path layout is altered, Node B becomes a transportation hub, increasing the flow of pedestrians through it. Node A, being on the edge of the site, has its path layout changes affecting only the flow around its vicinity, with minimal impact on other nodes. Node E, with existing paths on both the north and east sides, does not experience a significant change in the surrounding pedestrian flow distribution when additional paths are added to either side.

Observations indicate that the orientation of paths around nodes in MUGS significantly influences the distribution of pedestrian traffic. Notably, when nodes are centrally located, their impact on the total pedestrian count within the node is most pronounced. For new green space design, focusing on the central node design can enhance traffic flow and meet the needs of traversing individuals. Strategic placement and optimization of central nodes, along with the surrounding path structure, can effectively manage pedestrian movement and mitigate activity conflicts, thereby improving node vitality and efficiency. In the context of green space renovations, a comprehensive assessment of the current layout is essential.

By identifying areas prone to congestion or uneven distribution of pedestrian activity, targeted interventions such as adding or reorienting paths at specific nodes can alleviate existing issues and optimize the utilization of the green space.

### *4.3. Limitations*

This study employs an agent-based model to investigate the correlation between the spatial layout of urban MUGS and the activities of the population within them. However, certain limitations persist in both the selection of the research subject and the methodology utilized.

Regarding the research subject, the choice of 511 Park in the densely populated urban area of Nanjing was made. While the park is surrounded by a vibrant residential area and exhibits a distinct spatial pattern of paths and nodes within its green space, it is crucial to acknowledge the inherent variability among different MUGS. Factors such as location, surrounding environment, site layout, and size contribute to variations in population size and activity types within these spaces. Therefore, future research could benefit from considering a broader array of factors, including the location of MUGS, characteristics of the surrounding environment, and green space size. Such considerations would enable the extraction of diverse spatial patterns of MUGS, facilitating further analysis and validation across a more representative research sample.

Concerning the methodology, this study categorized population greenspace activities into five types, with data collection conducted at 15-minute intervals. However, the intricacies of population activities within MUGS are characterized by their complexity and diversity, often exhibiting instantaneous and stochastic behavior. While the study broadly covers population activities and behavior changes within MUGS during typical time periods on weekdays and weekends, certain limitations persist. Future research endeavors could entail a more nuanced classification of population activities and distribution periods. This study's approach to characterizing the crowd did not account for the nuances of demographic attributes such as gender, age, occupation, and income, which may significantly affect the way individuals engage with green spaces, their movement patterns, and density. The distinct behaviors of individuals could be shaped by these attributes. Subsequent studies could benefit from incorporating comprehensive surveys and interviews to delve into the specific behaviors of different demographic groups, such as the elderly or women. This line of inquiry could refine the planning and enhancement of MUGS, offering insights into creating "age-friendly" and "women-friendly" green environments, thereby guiding the development of superior green spaces.

## 5. Conclusions

In densely populated urban areas, the significance of MUGS as pivotal spatial entities accommodating population activities underscores the need to explore their spatial layout and its correlation with such activities. This study employs field survey alongside simulations of population behavior under varying flow volumes and layout configurations in MUGS, establishing a research framework applicable to MUGS. A typical MUGS in Nanjing was chosen as the study area. Systematic surveys of the population in this green space were conducted during different typical time periods on weekdays and weekends, identifying five typical green space activities. Subsequently, leveraging an agent-based model, a simulation platform for spatial population behavior in MUGS was developed.

By manipulating the layout of various elements within MUGS to generate multiple spatial scenarios, simulations of population green space activities were performed, followed by comparative analysis. The findings reveal a certain degree of correlation between the spatial layout of MUGS and people's activities, particularly evident in factors such as paths and entrances. Unlike other types of green spaces, neither node area nor the number of green space facilities significantly influences population activities and flow distribution within MUGS. Further discussion emphasizes the profound impact of path orientation on the distribution of population green-space activities within different nodes in MUGS.

This study on the relationship between population green space activities and the layout and elements of MUGS will provide valuable insights for landscape designers, aiding informed decision-making during the construction, renovation, and management of MUGS. At the current stage, targeted enhancement suggestions can be proposed for Park 511. Specifically, we have increased the unit area within Node E of the park by 20% and added two pathways, each 4 m wide, surrounding Node B. Through computational simulation, based on the aforementioned optimization model, the area south of Node B, which was previously underutilized in terms of pedestrian activity, saw an approximate increase of 30% in pedestrian flow. The construction regulations for MUGS in Nanjing explicitly stipulate that the facilities and layout of pocket parks, regardless of size, should meet the public's need for convenient usage. This includes ensuring adequate paved areas and a sufficient number of pathways, while also aiming to reduce park construction costs. To achieve this, it is essential to establish an assessment system and simulation methods that correspond with the behavioral characteristics of users before initiating the construction of pocket parks. Furthermore, larger pocket parks, such as Park 511, which ranges from 0.5 to 1 hectare in size, should incorporate well-planned landscape pathways and emergency evacuation routes to enhance safety and functionality. In future research and application scenarios, the multiperiod and multitype activity simulation paths and data results employed in this study can be further enhanced from various aspects, such as population activity attributes. Additionally, they can be integrated with different application scenarios, such as post-use evaluation of MUGS and assessment of their age-friendliness, catering to diverse research and practical needs. By focusing on the demands of population green-space activities, this research contributes to improving the allocation of mini green space resources in high-density urban environments.

**Author Contributions:** Conceptualization, S.C.; methodology, S.C., D.Z. and X.Z.; software, S.C.; formal analysis, D.Z., X.Z. and S.C.; investigation, S.C. and D.Z.; resources, S.C.; data curation, D.Z. and S.C.; writing—original draft preparation, S.C., D.Z. and X.Z.; writing—review and editing, Y.W., X.Z. and S.C.; visualization, S.C. and D.Z.; funding acquisition, S.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Fundamental Research Funds for the Central Universities, grant number 2242021R20016; Jiangsu Planned Projects for Postdoctoral Research Funds, grant number 2021K024A; China Postdoctoral Science Foundation, grant number 2021M700767; China Postdoctoral Science Foundation, grant number 2022T150115; National Natural Science Foundation of China, grant number 52108045; China Scholarship Council, grant number 202206090038 and the Scholarship for Visiting Scholars of Key Laboratory of New Technology for Construction of Cities in Mountain Area (LNTCCMA-20240106).

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Nordh, H.; Hartig, T.; Hagerhall, C.M.; Fry, G. Components of Small Urban Parks That Predict the Possibility for Restoration. *Urban For. Urban Green.* **2009**, *8*, 225–235. [CrossRef]
2. Peschardt, K.K.; Stigsdotter, U.K. Associations between Park Characteristics and Perceived Restorativeness of Small Public Urban Green Spaces. *Landsc. Urban Plan.* **2013**, *112*, 26–39. [CrossRef]
3. Bedimo-Rung, A.L.; Mowen, A.J.; Cohen, D.A. The Significance of Parks to Physical Activity and Public Health: A Conceptual Model. *Am. J. Prev. Med.* **2005**, *28*, 159–168. [CrossRef]
4. Peschardt, K.K.; Stigsdotter, U.K.; Schipperrijn, J. Identifying Features of Pocket Parks That May Be Related to Health Promoting Use. *Landsc. Res.* **2016**, *41*, 79–94. [CrossRef]
5. Astell-Burt, T.; Feng, X.; Mavoa, S.; Badland, H.M.; Giles-Corti, B. Do Low-Income Neighbourhoods Have the Least Green Space? A Cross-Sectional Study of Australia's Most Populous Cities. *BMC Public Health* **2014**, *14*, 292. [CrossRef]
6. Lin, W.; Chen, Q.; Jiang, M.; Zhang, X.; Liu, Z.; Tao, J.; Wu, L.; Xu, S.; Kang, Y.; Zeng, Q. The Effect of Green Space Behaviour and per Capita Area in Small Urban Green Spaces on Psychophysiological Responses. *Landsc. Urban Plan.* **2019**, *192*, 103637. [CrossRef]
7. Armato, F. Pocket Park: Product Urban Design. *Des. J.* **2017**, *20*, S1869–S1878. [CrossRef]

8. Foster, J. Hiding in Plain View: Vacancy and Prospect in Paris' Petite Ceinture. *Cities* **2014**, *40*, 124–132. [CrossRef]
9. Kerishnan, P.B.; Maruthaveeran, S.; Maulan, S. Investigating the Usability Pattern and Constraints of Pocket Parks in Kuala Lumpur, Malaysia. *Urban For. Urban Green.* **2020**, *50*, 126647. [CrossRef]
10. Nordh, H.; Østby, K. Pocket Parks for People—A Study of Park Design and Use. *Urban For. Urban Green.* **2013**, *12*, 12–17. [CrossRef]
11. Dong, J.; Guo, R.; Guo, F.; Guo, X.; Zhang, Z. Pocket Parks—A Systematic Literature Review. *Environ. Res. Lett.* **2023**, *18*, 083003. [CrossRef]
12. Zhang, H.; Han, M. Pocket Parks in English and Chinese Literature: A Review. *Urban For. Urban Green.* **2021**, *61*, 127080. [CrossRef]
13. American Planning Association. (1965, January). Standards for Outdoor Recreational Areas [Information Report No. 194]. American Society of Planning Officials. Available online: https://www.planning.org/pas/reports/report194.htm (accessed on 5 June 2024).
14. The Trust for Public Land. Pocket Park Toolkit [Brochure]. San Francisco, CA, USA. 2020. Available online: https://www.tpl.org/resource/pocket-park-toolkit (accessed on 5 June 2024).
15. Greater London Authority. The London Plan: Spatial Development Strategy for Greater London. 2008. Available online: https://www.london.gov.uk/thelondonplan (accessed on 5 June 2024).
16. Environmental Partnership (NSW) Pty Ltd. *Western Precinct Open Space and Landscape Masterplan*; Environmental Partnership (NSW) Pty Ltd.: Sydney, Australia, 2008. Available online: https://www.penrithcity.nsw.gov.au/images/documents/building-development/planning-zoning/planning-controls/Western_Precinct_Plan_Part_Q.pdf (accessed on 5 June 2024).
17. Ministry of Construction of the People's Republic of China. *Code of Urban Residential Areas Planning & Design GB 50180-93*; Ministry of Construction of the People's Republic of China: Beijing, China, 2002. Available online: https://www.planning.org.cn/law/uploads/2013/1383999145.pdf (accessed on 5 June 2024).
18. Jiangsu Provincial Department of Housing and Urban-Rural Development. *Standard for Greening of Resi-Dential Districts and Companies in Jiangsu Province*; Jiangsu Provincial Department of Housing and Urban-Rural Development: Nantong, China, 2014. Available online: https://ylj.nanjing.gov.cn/njslhylj/202012/P020201204599630466774.pdf (accessed on 13 June 2024).
19. Jiangsu Provincial Department of Housing and Urban-Rural Development. *Pocket Park Guidance of Jiangsu (Trial 2022)*; Jiangsu Provincial Department of Housing and Urban-Rural Development: Nantong, China, 2022.
20. Nanjing Municipal Bureau of Greening and Gardening. *Pocket Park Guidance of Nanjing (Trial)*; Nanjing Municipal Bureau of Greening and Gardening: Nanjing, China, 2023. Available online: https://ylj.nanjing.gov.cn/njslhylj/202305/P020230504565809200902.pdf (accessed on 5 June 2024).
21. Lee, J.; Tsunetsugu, Y.; Takayama, N.; Park, B.-J.; Li, Q.; Song, C.; Komatsu, M.; Ikei, H.; Tyrväinen, L.; Kagawa, T.; et al. Influence of Forest Therapy on Cardiovascular Relaxation in Young Adults. *Evid. Based Complement. Alternat. Med.* **2014**, *2014*, 834360. [CrossRef]
22. Liu, S.; Wang, X. Reexamine the Value of Urban Pocket Parks under the Impact of the COVID-19. *Urban For. Urban Green.* **2021**, *64*, 127294. [CrossRef]
23. Hartig, T.; Mitchell, R.; De Vries, S.; Frumkin, H. Nature and Health. *Annu. Rev. Public Health* **2014**, *35*, 207–228. [CrossRef]
24. Peng, H.; Li, X.; Yang, T.; Tan, S. Research on the Relationship between the Environmental Characteristics of Pocket Parks and Young People's Perception of the Restorative Effects—A Case Study Based on Chongqing City, China. *Sustainability* **2023**, *15*, 3943. [CrossRef]
25. Song, C.; Joung, D.; Ikei, H.; Igarashi, M.; Aga, M.; Park, B.-J.; Miwa, M.; Takagaki, M.; Miyazaki, Y. Physiological and Psychological Effects of Walking on Young Males in Urban Parks in Winter. *J. Physiol. Anthropol.* **2013**, *32*, 18. [CrossRef]
26. Song, C.; Ikei, H.; Igarashi, M.; Miwa, M.; Takagaki, M.; Miyazaki, Y. Physiological and Psychological Responses of Young Males during Spring-Time Walks in Urban Parks. *J. Physiol. Anthropol.* **2014**, *33*, 8. [CrossRef]
27. Bajwoluk, T.; Langer, P. The Pocket Park and Its Impact on the Quality of Urban Space on the Local and Supralocal Scale—Case Study of Krakow, Poland. *Sustainability* **2023**, *15*, 5153. [CrossRef]
28. Huang, Y.; Lin, X.; Lin, S.; Chen, Z.; Fu, W.; Wang, M.; Dong, J. Pocket Parks: A New Approach to Improving the Psychological and Physical Health of Recreationists. *Forests* **2023**, *14*, 1983. [CrossRef]
29. Mu, B.; Liu, C.; Mu, T.; Xu, X.; Tian, G.; Zhang, Y.; Kim, G. Spatiotemporal Fluctuations in Urban Park Spatial Vitality Determined by On-Site Observation and Behavior Mapping: A Case Study of Three Parks in Zhengzhou City, China. *Urban For. Urban Green.* **2021**, *64*, 127246. [CrossRef]
30. Barton, H.; Grant, M.; Guise, R. *Shaping Neighbourhoods: For Local Health and Global Sustainability*, 3rd ed.; Routledge: London, UK, 2021; ISBN 978-0-429-32124-5.
31. Bernstein, F.A. Side Pocket: New York's Paley Park, Which Turns 50 This Month, Is a Masterpiece-Proof That Even a Tiny Public Space Can Make a Difference in a Crowded City. *Landsc. Archit.* **2017**, *107*, 122–129.
32. Dallimer, M.; Irvine, K.N.; Skinner, A.M.J.; Davies, Z.G.; Rouquette, J.R.; Maltby, L.L.; Warren, P.H.; Armsworth, P.R.; Gaston, K.J. Biodiversity and the Feel-Good Factor: Understanding Associations between Self-Reported Human Well-Being and Species Richness. *BioScience* **2012**, *62*, 47–55. [CrossRef]
33. Gibson, H.; Canfield, J. Pocket Parks as Community Building Blocks: A Focus on Stapleton, CO. *Community Dev.* **2016**, *47*, 732–745. [CrossRef]
34. Strohbach, M.W.; Lerman, S.B.; Warren, P.S. Are Small Greening Areas Enhancing Bird Diversity? Insights from Community-Driven Greening Projects in Boston. *Landsc. Urban Plan.* **2013**, *114*, 69–79. [CrossRef]

35. Wang, X.; Li, G.; Pan, J.; Shen, J.; Han, C. The Difference in the Elderly's Visual Impact Assessment of Pocket Park Landscape. *Sci. Rep.* **2023**, *13*, 16895. [CrossRef]
36. Higueras, E.; Román, E.; Fariña, J. Guidelines for Healthier Public Spaces for the Elderly Population: Recommendations in the Spanish Context. In *Handbook of Quality of Life and Sustainability*; Martinez, J., Mikkelsen, C.A., Phillips, R., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 35–51, ISBN 978-3-030-50540-0.
37. Kaplan, R. The Analysis of Perception via Preference: A Strategy for Studying How the Environment Is Experienced. *Landsc. Plan.* **1985**, *12*, 161–176. [CrossRef]
38. Chen, Y.; Liu, X.; Gao, W.; Wang, R.Y.; Li, Y.; Tu, W. Emerging Social Media Data on Measuring Urban Park Use. *Urban For. Urban Green.* **2018**, *31*, 130–141. [CrossRef]
39. Cohen, D.A.; Han, B.; Derose, K.P.; Williamson, S.; Marsh, T.; Raaen, L.; McKenzie, T.L. Promoting Physical Activity in High-Poverty Neighborhood Parks: A Cluster Randomized Controlled Trial. *Soc. Sci. Med.* **2017**, *186*, 130–138. [CrossRef]
40. Hong, X.-C.; Cheng, S.; Liu, J.; Guo, L.-H.; Dang, E.; Wang, J.-B.; Cheng, Y. How Should Soundscape Optimization from Perceived Soundscape Elements in Urban Forests by the Riverside Be Performed? *Land* **2023**, *12*, 1929. [CrossRef]
41. Hazer, M.; Formica, M.K.; Dieterlen, S.; Morley, C.P. The Relationship between Self-Reported Exposure to Greenspace and Human Stress in Baltimore, MD. *Landsc. Urban Plan.* **2018**, *169*, 47–56. [CrossRef]
42. Song, C.; Ikei, H.; Miyazaki, Y. Physiological Effects of Nature Therapy: A Review of the Research in Japan. *Int. J. Environ. Res. Public Health* **2016**, *13*, 781. [CrossRef]
43. Baur, J.W.R.; Tynon, J.F. Small-Scale Urban Nature Parks: Why Should We Care? *Leis. Sci.* **2010**, *32*, 195–200. [CrossRef]
44. Nordh, H. Restorative Components of Small Urban Parks. Ph.D. Thesis, Norwegian University of Life Sciences, Ås, Norway, 2010.
45. Sullivan, W.C.; Kuo, F.E.; Depooter, S.F. The Fruit of Urban Nature: Vital Neighborhood Spaces. *Environ. Behav.* **2004**, *36*, 678–700. [CrossRef]
46. Gómez, E.; Baur, J.W.R.; Hill, E.; Georgiev, S. Urban Parks and Psychological Sense of Community. *J. Leis. Res.* **2015**, *47*, 388–398. [CrossRef]
47. Harnik, P. *Urban Green: Innovative Parks for Resurgent Cities*; Island Press: Washington, DC, USA, 2012; ISBN 978-1-59726-812-7.
48. Zhou, C.; Fu, L.; Xue, Y.; Wang, Z.; Zhang, Y. Using Multi-Source Data to Understand the Factors Affecting Mini-Park Visitation in Yancheng. *Environ. Plan. B Urban Anal. City Sci.* **2022**, *49*, 754–770. [CrossRef]
49. Yang, B.; Hong, B. Pocket Park in Urban Regeneration of China: Policy and Perspective. *City Environ. Interact.* **2023**, *19*, 100109. [CrossRef]
50. Zhou, C.; An, Y.; Zhao, J.; Xue, Y.; Fu, L. How Do Mini-Parks Serve in Groups? A Visit Analysis of Mini-Park Groups in the Neighbourhoods of Nanjing. *Cities* **2022**, *129*, 103804. [CrossRef]
51. Xu, X.; Sun, S.; Liu, W.; García, E.H.; He, L.; Cai, Q.; Xu, S.; Wang, J.; Zhu, J. The Cooling and Energy Saving Effect of Landscape Design Parameters of Urban Park in Summer: A Case of Beijing, China. *Energy Build.* **2017**, *149*, 91–100. [CrossRef]
52. Xu, X.; Liu, S.; Sun, S.; Zhang, W.; Liu, Y.; Lao, Z.; Guo, G.; Smith, K.; Cui, Y.; Liu, W.; et al. Evaluation of Energy Saving Potential of an Urban Green Space and Its Water Bodies. *Energy Build.* **2019**, *188–189*, 58–70. [CrossRef]
53. Luo, Y.; Zhang, L. Analysis of Crowd Movement Based on Mobile Phone Signaling. *Int. J. Sci.* **2018**, *5*, 227–234.
54. Qin, S.; Man, J.; Wang, X.; Li, C.; Dong, H.; Ge, X. Applying Big Data Analytics to Monitor Tourist Flow for the Scenic Area Operation Management. *Discrete Dyn. Nat. Soc.* **2019**, *2019*, 8239047. [CrossRef]
55. Wu, C.; Chen, D. Tourist versus Resident Movement Patterns in Open Scenic Areas: Case Study of Confucius Temple Scenic Area, Nanjing, China. *Int. J. Tour. Res.* **2021**, *23*, 1163–1175. [CrossRef]
56. Adrianto, L.; Kurniawan, F.; Romadhon, A.; Bengen, D.G.; Sjafrie, N.D.M.; Damar, A.; Kleinertz, S. Assessing Social-Ecological System Carrying Capacity for Urban Small Island Tourism: The Case of Tidung Islands, Jakarta Capital Province, Indonesia. *Ocean Coast. Manag.* **2021**, *212*, 105844. [CrossRef]
57. Wang, Y.; Xie, T.; Jie, X. A Mathematical Analysis for the Forecast Research on Tourism Carrying Capacity to Promote the Effective and Sustainable Development of Tourism. *Discrete Contin. Dyn. Syst.-Ser. S* **2019**, *12*, 837–847. [CrossRef]
58. Zhang, Y.; Li, X.R.; Su, Q.; Hu, X. Exploring a Theme Park's Tourism Carrying Capacity: A Demand-Side Analysis. *Tour. Manag.* **2017**, *59*, 564–578. [CrossRef]
59. Ann, W. Discrete-Event Simulation of Air Traffic Movements in the Mexican Metropolitan Airspace. *Transp. Res. Procedia* **2021**, *56*, 39–46. [CrossRef]
60. Leka, A.; Lagarias, A.; Panagiotopoulou, M.; Stratigea, A. Development of a Tourism Carrying Capacity Index (TCCI) for Sustainable Management of Coastal Areas in Mediterranean Islands–Case Study Naxos, Greece. *Ocean Coast. Manag.* **2022**, *216*, 105978. [CrossRef]
61. Stewart, A.; Elyan, E.; Isaacs, J.; McEwen, L.; Wilson, L. The Effect of Person Order on Egress Time: A Simulation Model of Evacuation from a Neolithic Visitor Attraction. *Hum. Factors* **2017**, *59*, 1222–1232. [CrossRef]
62. Widz, M.; Brzezińska-Wójcik, T. Assessment of the Overtourism Phenomenon Risk in Tunisia in Relation to the Tourism Area Life Cycle Concept. *Sustainability* **2020**, *12*, 2004. [CrossRef]
63. He, B.; Hu, J.; Liu, K.; Xue, J.; Ning, L.; Fan, J. Exploring Park Visit Variability Using Cell Phone Data in Shenzhen, China. *Remote Sens.* **2022**, *14*, 499. [CrossRef]

64. Lee, C.-S.; Chang, Y.-C.; Wang, M.-H. Ontological Recommendation Multi-Agent for Tainan City Travel. *Expert Syst. Appl.* **2009**, *36*, 6740–6753. [CrossRef]
65. Li, J. Dynamic Visiting Coordination Problem Based on Multi-Agent for Large-Scale Crowds' Activities. *Int. J. Ind. Syst. Eng.* **2014**, *17*, 115–131. [CrossRef]
66. Shen, N.; Zhang, H.; Wang, H.; Zhou, X.; Zhou, L.; Tang, G. Toward Multi-Granularity Spatiotemporal Simulation Modeling of Crowd Movement for Dynamic Assessment of Tourist Carrying Capacity. *GIScience Remote Sens.* **2022**, *59*, 1857–1881. [CrossRef]
67. Gao, F.; Liao, S.; Wang, Z.; Cai, G.; Feng, L.; Yang, Z.; Chen, W.; Chen, X.; Li, G. Revealing Disparities in Different Types of Park Visits Based on Cellphone Signaling Data in Guangzhou, China. *J. Environ. Manag.* **2024**, *351*, 119969. [CrossRef] [PubMed]
68. Nordh, H.; Alalouch, C.; Hartig, T. Assessing Restorative Components of Small Urban Parks Using Conjoint Methodology. *Urban For. Urban Green.* **2011**, *10*, 95–103. [CrossRef]
69. Safaie Ghamsary, E.; Karimimoshaver, M.; Akhavan, A.; Afzali Goruh, Z.; Aram, F.; Mosavi, A. Locating Pocket Parks: Assessing the Effects of Land Use and Accessibility on the Public Presence. *Environ. Sustain. Indic.* **2023**, *18*, 100253. [CrossRef]
70. Salih, S.A.; Ismail, S.; Mseer, A. Pocket Parks for Promoting Social Interaction among Residents of Baghdad City. *Archnet-IJAR Int. J. Archit. Res.* **2020**, *14*, 393–408. [CrossRef]
71. Yeh, M.L.; Chou, Y.T.; Yang, L.S. The Evaluation of GPS Techniques for UAV-Based Photogrammetry in Urban Area. *ISPRS-Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *XLI-B1*, 1079–1084. [CrossRef]
72. Klosterman, S.; Melaas, E.; Wang, J.A.; Martinez, A.; Frederick, S.; O'Keefe, J.; Orwig, D.A.; Wang, Z.; Sun, Q.; Schaaf, C. Fine-Scale Perspectives on Landscape Phenology from Unmanned Aerial Vehicle (UAV) Photography. *Agric. For. Meteorol.* **2018**, *248*, 397–407. [CrossRef]
73. Lendzioch, T.; Langhammer, J.; Jenicek, M. Tracking Forest and Open Area Effects on Snow Accumulation by Unmanned Aerial Vehicle Photogrammetry. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *XLI-B1*, 917–923. [CrossRef]
74. Park, K.; Ewing, R. The Usability of Unmanned Aerial Vehicles (UAVs) for Measuring Park-Based Physical Activity. *Landsc. Urban Plan.* **2017**, *167*, 157–164. [CrossRef]
75. Carver, S.; Quincey, D. A Conceptual Framework of Volcanic Evacuation Simulation of Merapi Using Agent-Based Model and GIS. *Procedia-Soc. Behav. Sci.* **2016**, *227*, 402–409.
76. Chen, Y.; Yang, J. Historic Neighborhood Design Based on Facility Heatmap and Pedestrian Simulation: Case Study in China. *J. Urban Plan. Dev.* **2020**, *146*, 04020001. [CrossRef]
77. Jia, S.; Wang, Y. Effect of Heat Mitigation Strategies on Thermal Environment, Thermal Comfort, and Walkability: A Case Study in Hong Kong. *Build. Environ.* **2021**, *201*, 107988. [CrossRef]
78. Song, S.; Leng, H.; Guo, R. Multi-Agent-Based Model for the Urban Macro-Level Impact Factors of Building Energy Consumption on Different Types of Land. *Land* **2022**, *11*, 1986. [CrossRef]
79. Tzvetanov, K.; Riegsecker, A.; Frantz, B.; Xiong, C.; Bott, R.; Cline, T.; Dubiel, B.; Dietz, J.E. Agent-Based Modeling for Theme Park Evacuation. *J. Emerg. Manag. West. Mass* **2022**, *20*, 157–173. [CrossRef]
80. Giles-Corti, B.; Broomhall, M.H.; Knuiman, M.; Collins, C.; Douglas, K.; Ng, K.; Lange, A.; Donovan, R.J. Increasing Walking: How Important Is Distance to, Attractiveness, and Size of Public Open Space? *Am. J. Prev. Med.* **2005**, *28*, 169–176. [CrossRef]
81. Owen, N.; Humpel, N.; Leslie, E.; Bauman, A.; Sallis, J.F. Understanding Environmental Influences on Walking: Review and Research Agenda. *Am. J. Prev. Med.* **2004**, *27*, 67–76. [CrossRef]
82. Wang, T.; Li, Y.; Li, H.; Chen, S.; Li, H.; Zhang, Y. Research on the Vitality Evaluation of Parks and Squares in Medium-Sized Chinese Cities from the Perspective of Urban Functional Areas. *Int. J. Environ. Res. Public Health* **2022**, *19*, 15238. [CrossRef]
83. Zuo, J.; Shi, J.; Li, C.; Mu, T.; Zeng, Y.; Dong, J. Simulation and Optimization of Pedestrian Evacuation in High-Density Urban Areas for Effectiveness Improvement. *Environ. Impact Assess. Rev.* **2021**, *87*, 106521. [CrossRef]
84. Xu, H.; Tian, C.; Li, Y. Emergency Evacuation Simulation and Optimization for a Complex Rail Transit Station: A Perspective of Promoting Transportation Safety. *J. Adv. Transp.* **2020**, *2020*, 8791503. [CrossRef]
85. Li, X.; Lv, Z.; Zheng, Z.; Zhong, C.; Hijazi, I.H.; Cheng, S. Assessment of Lively Street Network Based on Geographic Information System and Space Syntax. *Multimed. Tools Appl.* **2017**, *76*, 17801–17819. [CrossRef]
86. Mohamed, A.A.; Kronenberg, J.; Łaszkiewicz, E. Integrating Space Syntax with Field Observations to Understand the Spatial Logic of Park Infrastructure. *J. Asian Archit. Build. Eng.* **2023**, 1–19. [CrossRef]
87. Mohammadi Tahroodi, F.; Ujang, N. Engaging in Social Interaction: Relationships between the Accessibility of Path Structure and Intensity of Passive Social Interaction in Urban Parks. *Archnet-IJAR Int. J. Archit. Res.* **2022**, *16*, 112–133. [CrossRef]
88. Zhai, Y.; Baran, P.K.; Wu, C. Can Trail Spatial Attributes Predict Trail Use Level in Urban Forest Park? An Examination Integrating GPS Data and Space Syntax Theory. *Urban For. Urban Green.* **2018**, *29*, 171–182. [CrossRef]
89. Jim, C.Y.; Chen, W.Y. Recreation–Amenity Use and Contingent Valuation of Urban Greenspaces in Guangzhou, China. *Landsc. Urban Plan.* **2006**, *75*, 81–96. [CrossRef]
90. Zhang, S.; Zhou, W. Recreational Visits to Urban Parks and Factors Affecting Park Visits: Evidence from Geotagged Social Media Data. *Landsc. Urban Plan.* **2018**, *180*, 27–35. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

buildings

MDPI

*Hypothesis*

# Relationships between Green Space Perceptions, Green Space Use, and the Multidimensional Health of Older People: A Case Study of Fuzhou, China

**Yuanjing Wu [1], Wei Zhou [1,2], Huimin Zhang [1], Qunyue Liu [3], Zhao Yan [4] and Siren Lan [1,*]**

[1] College of Landscape Architecture and Art, Fujian Agriculture and Forestry University, 15 Shangxiadian Road, Fuzhou 350002, China; yuanjingwu@fafu.edu.cn (Y.W.); zzzzwei1@student.ubc.ca (W.Z.); 5221726052@fafu.edu.cn (H.Z.)
[2] Faculty of Forestry, The University of British Columbia, 2329 West Mall Vancouver, Vancouver, BC V6T 1Z4, Canada
[3] College of Architecture and Urban Planning, Fujian University of Technology, 33 Xuefu South Road, Fuzhou 350118, China; fjlqy@fjut.edu.cn
[4] Fuzhou Minhou County Shangyi Education Technology Co., Ltd., Fuzhou 350108, China
* Correspondence: lkzx@fafu.edu.cn

**Abstract:** Urban green spaces are vital for older people's health. However, most studies have only focused on their relationship with single-dimensional health outcomes. This study introduced a theoretical model to explore how perceptions of green spaces influence older people's multidimensional health, mediated by the use of these spaces. Using a literature review, interviews, and surveys, we developed and refined a measurement scale for older people's perceptions of urban greenery. Using data from 513 seniors in Fuzhou's urban parks, structural equation modeling was used to examine the relationships between their multidimensional health, usage, and perceptions of green spaces. The results showed that older people's positive evaluations of green spaces, especially those with facilities, significantly increased their usage. This increased usage positively influences their physical, mental, and social health, with the most pronounced benefits for social health. The total impact of green space perception on multidimensional health was beneficial and significantly impacted social health, even though the direct impacts of quality perception on physical health and facility perception on social health were minimal. These findings enhance our understanding of the impact of green spaces on the health of older individuals and provide a theoretical basis for developing urban green spaces that maximize health advantages for older people.

**Keywords:** green space perception; green space use; multidimensional health; older people; influence mechanism; structural equation modeling

**Citation:** Wu, Y.; Zhou, W.; Zhang, H.; Liu, Q.; Yan, Z.; Lan, S. Relationships between Green Space Perceptions, Green Space Use, and the Multidimensional Health of Older People: A Case Study of Fuzhou, China. *Buildings* **2024**, *14*, 1544. https://doi.org/10.3390/buildings14061544

Academic Editor: Derek Clements-Croome

Received: 29 April 2024
Revised: 16 May 2024
Accepted: 20 May 2024
Published: 27 May 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The worldwide population of older people exceeded 760 million in 2021 and is expected to more than double by 2050, indicating an unparalleled global aging trend [1]. China has the largest population of older people and one of the fastest aging rates in the world [2]. According to data from the seventh national census, the population of individuals in China who are 65 years old and over was 19.064 million, accounting for 13.5% of the total population. The population aged 60 and above is expected to reach 300 million in 2025 and close to 500 million by mid-century, accounting for 35% of China's total population. This would lead to China being a super-aging country [3]. This demographic change has made the health of older people a primary focus of social concerns, highlighting the importance of developing conditions that improve their quality of life. Parks and green spaces have a crucial role in enhancing the quality of life and fostering the well-being of older individuals, as integral components of the urban environment [4]. When compared with other age groups, older people use urban green spaces for activities more frequently [5].

Therefore, exploring the relationship between older people's perceptions, use, and health benefits from green spaces is essential.

In recent times, there has been an increase in research focusing on the beneficial impacts of the green spaces in parks on the physical and emotional well-being of older individuals. These benefits include enhancing their levels of physical activity, reducing psychological stress, and promoting social connection [6,7]. Green spaces can reduce stress by improving people's quality of life and reducing their levels of depression and anxiety [8]. High-quality green spaces in a neighborhood are associated with higher physical activity levels and improved self-assessed health [9,10]. Furthermore, middle-aged and older people have a greater amount of leisure time, resulting in a greater desire for natural surroundings and a healthy lifestyle. As a result, they constitute a significant portion of the population that actively utilizes urban green areas [11]. This is motivated by relaxation, activity, and proximity to nature for leisure purposes [12]. The health and well-being of older individuals are strongly influenced by their perceptions and utilization patterns of park green areas. Their perceptions of green spaces, including factors such as how easily accessible they are, the quality of their facilities, and the level of environmental safety, substantially impact their willingness and frequency of using these areas. As a result, these perceptions directly affect the actual usage of green spaces. High-quality green space environments can encourage older adults to engage in outdoor activities more frequently [13]. The health benefits of green spaces include increased physical activity, stress reduction, and recreational and sporting activities [14]. The regular use of parks and green spaces by older adults is associated with lower stress levels, improved mood, and improved mental health.

Moreover, parks and green spaces provide an escape from the stresses of daily life and enhance psychological resilience [15]. Furthermore, older individuals use park green spaces that offer opportunities to participate in physical exercise and encourage social and community participation. Older persons who participate in green space activities demonstrate better social support and community involvement, which is crucial for their social well-being [16]. In addition, how older people perceive green spaces in parks and how these perceptions affect their health behaviors and psychological states [17] has received recent attention from scholars.

The majority of studies have examined the correlation between the green space environment, green space use (GSU), and one or two health dimensions separately, while only a limited number of studies have investigated the impact of green spaces on all three health dimensions simultaneously: mental, physical, and social health. The precise mechanisms underlying how older people's perceptions and use of green spaces in parks impact their multidimensional health are not fully understood. Further studies are required to improve park green space design and attitudes to promote park usage and multidimensional health in older adults. As previous studies have paid less attention to the impact of urban green spaces on the three dimensions of the mental, physical, and social health of older people, we attempted to explore this aspect. This study aimed to investigate how park green areas are perceived and used by older people, as well as how these characteristics affect their overall health. Using a theoretical model with GSU as a mediator, this study sought to establish a connection between multidimensional health and older adults' green space perceptions (GSPs). The objectives of this study were the following:

O1. Explore an indicator system for measuring older people's perceptions of green spaces.
O2. Explore the relationships between older adults' GSPs, GSU, and self-assessed multidimensional health.

The results of this study are expected to be used as a basis for developing age-friendly environments in urban parks, enhancing the health of older individuals, and improving the overall experience for the elderly population.

## 2. Theoretical Analysis and Hypotheses

### *2.1. Green Space Perception concerning Green Space Use*

The existing research has demonstrated a strong link between residents' perceptions of green spaces and their GSU behavior [18]. The perception of green spaces directly affects the frequency and duration of visits by older people to urban green spaces [17]. The attractiveness, pleasure, and safety of urban green spaces have been found to motivate people to use these spaces [19,20]. For instance, research has shown that older people's perceptions of the safety and accessibility of urban green spaces influence their GSU frequency and self-rated health [21]. People who believe green spaces are safe places to hang out are more inclined to participate in outdoor activities and recreation there [22]. They might stop using the green area altogether or change how often they utilize it if they believe it is risky [23]. In addition, the quality and quantity of the facilities are also essential factors that affect older people's willingness to visit a green space for different activities [24,25]. Older people are more likely to use green spaces frequently for physical exercise and leisure activities if they perceive the green space to be easy to reach and accessible [26,27]. The perceptions of older individuals about the qualitative characteristics of green spaces, such as aesthetics and maintenance condition, have a substantial impact on their propensity to utilize these areas. Thus, this directly influences their actual usage of green spaces. Therefore, well-maintained green areas can motivate elderly individuals to participate in more frequent outdoor activities [13].

Moreover, it is crucial to consider the emotional perception of green spaces, which refers to how older people perceive the opportunities for social connection in green areas. The development of favorable feelings towards green spaces can affect the amount of time elderly individuals spend in green areas. People perceive that green spaces are locations that encourage social relationships, and they are especially noteworthy for their ability to reduce feelings of isolation among older persons [28]. Furthermore, by comparing different parks, it was found that the various facilities provided in parks, such as running trails, fitness equipment, and basketball courts, increased park usage [29]. According to the findings of these studies, the views of older people on the quality of green spaces, their perceptions of the facilities, their perceptions of their experiences, and their perceptions of their emotions all directly influence the amount of time they spend in green spaces. Therefore, in light of these results, the current research offers the following hypothesis:

**Hypothesis 1 (H1).** *Older people's GSPs have a significant positive impact on their GSU.*

### *2.2. Green Space Use concerning Health*

Green space use positively impacts the general health of older adults, with older adults with regular access to and use of green space having significantly better self-rated health status than those with less access to green spaces [30]. Studies have shown that exercise in green spaces improves the physiological health, such as lowering blood pressure and reducing the risk of chronic disease, of older people [31]. Moreover, older individuals demonstrate enhanced cardiovascular health indicators, such as reduced blood pressure and heart rate variability. These findings indicate that green spaces offer a favorable context for maintaining cardiovascular well-being [32]. Different types of green space activities can promote older people's health in various ways. For instance, recreational activities, such as picnicking and reading [22], and light physical activities, such as walking, jogging, tai chi [33], and gardening [31], in green spaces can significantly reduce the risk of health problems, such as diabetes, obesity, cardiovascular disease, and other chronic diseases [34], and improve physical health.

Exposure to green spaces may significantly enhance older people's mental health, including lowering their stress levels, improving their mood, and increasing well-being. This is particularly relevant when it comes to the impact that green space utilization has on mental health. The natural environment benefits the mental health and well-being of older people with disabilities [35]. Older people can significantly improve their mental

health through the use of green spaces, reducing symptoms of depression and anxiety and increasing life satisfaction and well-being. Overall, older people with regular access to green spaces report reduced stress levels and better mood states [36]. Moreover, gardening activities in green spaces can provide physical and mental relaxation, promoting health and well-being [37].

Concerning social health, green spaces provide places for older people to socialize and interact, which can help reduce loneliness and social isolation [38]. Older people who participate in green space activities score higher in social support and community involvement, which is crucial for their social health [16]. Hence, urban green areas are essential for promoting health and well-being by offering opportunities for physical exercise and social engagement [4]. The findings of these studies indicate that older individuals primarily participate in activities such as walking, gardening, relaxing, jogging, tai chi, and socializing when utilizing green spaces. These activities have a notable influence on the health of older individuals, as they contribute to physical well-being, enhance mental health, reduce stress levels, and facilitate social interactions. Therefore, based on these findings, this study proposed the following hypothesis:

**Hypothesis 2 (H2).** *Older people's GSU has a significant positive impact on their self-assessed physical health (PH), mental health (MH), and social health (SH).*

### *2.3. Green Space Perception concerning Health*

The perceptions of green spaces among older people, particularly their assessment and evaluation of their natural surroundings, directly and indirectly impact their health and overall well-being. Residents' physical and emotional health is enhanced when their desires for green space environments are fulfilled [39]. People's perceptions of green spaces can moderate the health benefits of urban green spaces [40]. Environmental factors and the quality of green spaces influence users' perceptions of and preferences for green spaces, thus affecting their health [41]. Environmental perception is one of the most critical factors affecting the mental health of residents [42], and green space environments with high perceptual ratings are more likely to promote stress reduction and improved mental health than those with low perceptual ratings [43]. As a result, enhancing urban green space quality may be a valuable strategy for addressing chronic health issues [44], and individual perceptions about the quality of green space can substantially impact this [45]. Thus, based on these findings, this study proposed the following hypothesis:

**Hypothesis 3 (H3).** *Older people's GSPs have a significant positive impact on their self-rated physical health, mental health, and social health.*

Furthermore, GSP has an indirect impact on health. The utilization of green space by individuals frequently acts as an intermediary element in the correlation between GSP and health [40]. The nature of individuals' activities when visiting green spaces plays a vital role in connecting urban green spaces with enhanced human health [46]. For example, people tend to have increased health when increasing the duration and intensity of their physical activity [47]. Older adults spend more time in parks compared to other age groups [48]. Thus, there is a stronger relationship between older people's perceptions of green spaces and their use of green spaces [17], and their physical health, mental health, and social health benefits are enhanced when using green spaces for activities [30]. The correlation between physical exercise and mental health is more substantial than that between social engagement and mental health in older persons [49]. An Australian study found a considerable association between residents' perceptions of communal green spaces and their self-rated mental health. This association was based on perceived environmental qualities, neighborhood satisfaction, and self-rated mental health [50]. In addition, the frequency of residents' activities in green spaces [51], the duration and type of activities, and the behavioral characteristics of the activities [46] have also been shown to be influenced

by the green space environment and their perceptual ratings of the environment, and these behavioral characteristics are associated with mental health [52]. Therefore, based on previous findings, this study proposed the following hypothesis:

**Hypothesis 4 (H4).** *GSU mediates older people's GSPs' influence on their self-assessed physical, mental, and social health.*

## 3. Materials and Methods

### *3.1. Study Area*

Fuzhou City is the capital of Fujian Province in China and is located in the lower reaches of the Min River, on the southeast coast. The problem of aging is becoming more prominent in Fuzhou. According to the seventh national census, about 16.76% of the population in Fuzhou is 60 years old and above, and 11.72% is 65 years old and above, which is 0.78% and 0.62% higher than the average level of the whole province of Fujian, respectively. Thus, there is an urgent need to address the health problems of older people. Furthermore, Fuzhou City has numerous urban green spaces and has earned the nickname "the city of a thousand gardens." This study selected urban parks of various sizes, including West Lake Park, Zuohai Park, Minjiang Park, and Jinshan Park, as sample sites for the survey. These parks were selected based on their alignment with the study's objectives, completion time, range, and their visitor flow (Figure 1).

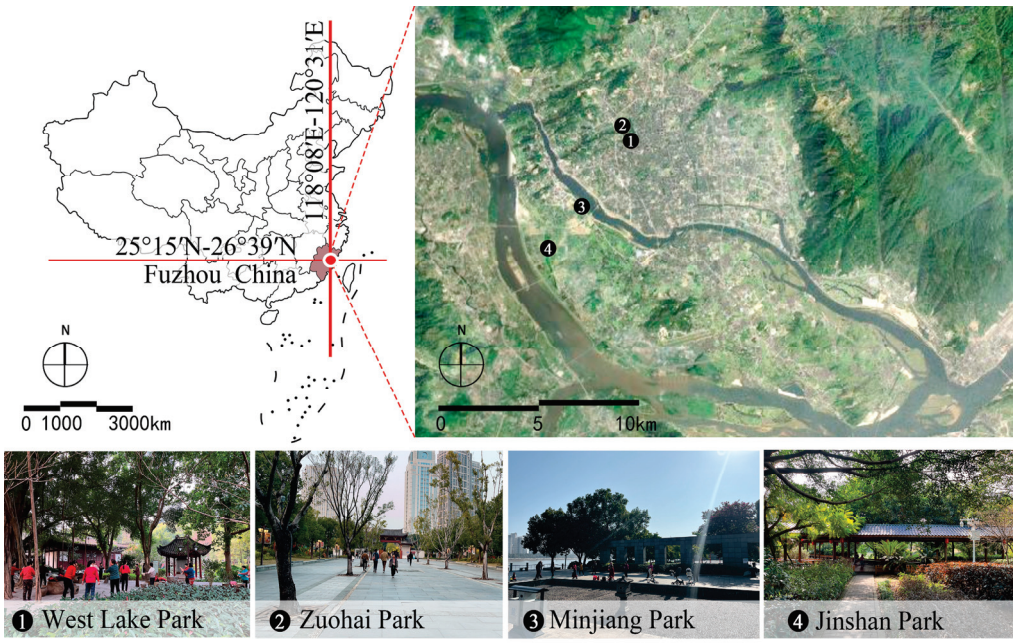



**Figure 1.** Study area.

### *3.2. Data Collection*

The survey was carried out on sunny days with comparable temperatures to reduce the impact of weather and temperature on the responses. It was directed at people 60 years of age and older who were taking leisure in four parks in Fuzhou City, and the participants provided their permission to participate. Based on random sampling and face-to-face interviews, the survey focused on perceptions of the urban park environment, activities, and health. Following structured interviews and a thematic analysis of the literature on park perception indicators, 20 indicators across four dimensions were identified. Moreover, a pre-questionnaire survey was also conducted. The team provided organizational training to the research team members. This study employs a paper-based methodology to address the possible challenges that elderly adults may face when reading surveys. A survey team member reads the questions and answers out loud one at a time, ensuring that respondents

comprehend them fully and provide accurate responses, thus improving the efficiency of the questionnaire process. Once elderly respondents answered all the questions, their questionnaires were deemed valid, and they received a small thank you gift. The survey was conducted in West Lake Park and Zuohai Park from 4–6 January 2024, and it yielded 87 valid responses, leading to questionnaire adjustments for clarity. The primary survey, conducted from 8 January to 5 February 2024, collected a total of 550 questionnaires. Of these, 513 replies were considered valid, resulting in a response rate of 93.3%. The data included personal information, decisions about park impressions, participation in activities, and self-assessments of health. The respondents comprised older adults of various genders, age groups, and housing arrangements, assuring a certain degree of representativeness.

Table 1 shows that, among the survey participants, 270 (52.6%) were male and 243 (47.4%) were female. Most participants in the random sample were concentrated in the age ranges of 60–70 and 71–80, which can be attributed to their increased physical activity and regular excursions to urban parks and green areas. In addition, the survey included 66 individuals between the ages of 81 and 90, accounting for 13% of the participants. Furthermore, 7 participants were over the age of 90, making up 1.4% of the total. Regarding living arrangements, the largest group, comprising 231 respondents (45.0%), lived with a partner, which was followed by 129 (25.1%) in three-generation households, 124 (24.2%) living with their children, and 27 (5.3%) living alone.

**Table 1.** Demographic information of the study sample.

| Variables | Title | Frequency | Surveyed (%) |
|---|---|---|---|
| Gender | Male | 270 | 52.6 |
| | Female | 243 | 47.4 |
| Age | 60 to 70 | 275 | 53.6 |
| | 71 to 80 | 165 | 32.2 |
| | 81 to 90 | 66 | 13 |
| | >90 | 7 | 1.4 |
| Living style | Lived with a partner | 231 | 45.0 |
| | Living with three generations of family | 129 | 25.1 |
| | Living with their children | 124 | 24.2 |
| | Living alone | 27 | 5.3 |
| | Others | 2 | 0.4 |

### *3.3. Variable Description*

This questionnaire, informed by in-depth interviews and prior research on older people's perceptions of urban park green spaces, their usage, and health, assessed the older people's GSP across four dimensions (quality, facilities, experience, and emotional connection), using 17 items. The ecological status, maintenance, richness, and attractiveness of the terrain were among the qualitative perceptions asked about. The suitability of the rest places, lighting, accessibility, recreational amenities, venue layout, and scale were the main areas of focus for their facility perceptions. The emotional perceptions examined security, familiarity, attachment, and belonging, while the experience perceptions addressed recreation, comfort, and accessibility. The dependent variable was self-assessed multidimensional health, which included self-assessed physical, mental, and social health based on existing studies' scales. The self-assessed physical health scale was designed with five items from the Health Survey SF-12 Short Form [53], and mental health was developed with six items from the same source; the social health scale included social relationships, social support, social connections, and social interactions, with four question items [54,55]. A 7-point Likert scale was used to measure the items above. The indicators that were precisely measured were the "weekly length of visits to green space", "weekly frequency of visits to green space," and "weekly total green space activity". GSU served as the mediating variable. The average activity metabolic equivalent was multiplied by the weekly activity hours of the older individuals to determine their total weekly activity in green spaces.

The questionnaire was used to determine the types of activities that older people conduct in green spaces, as shown in Table 2, which was based on a compilation of the physical activities of healthy adults in China [56]. The behavioral activities of elderly individuals in urban parks were observed and categorized. Metabolic equivalents were assigned to these activities to determine their average metabolic equivalents. The three indicators were classified into 7 levels to facilitate their study. In addition, the questionnaire included questions on the respondents' basic personal information, their mode of residence, purpose in visiting the park, time of visiting the park, companions visiting the park, and mode of visiting the park, which were answered in a multiple-choice format.

**Table 2.** Classification of everyday activities of older people in urban parks.

| Activity Category | Code | Metabolic Equivalent of Task (MET) | Specific Activity |
|---|---|---|---|
| Inactivity, rest/low-intensity activity | CHN01002 | 1.6 | Standing quietly: general/leaning/**watching others' activities** |
| | CHN01003 | 1.3 | Sitting quietly: general/leaning/**watching others' activities** |
| | CHN01004 | 1.1 | Reading books/**newspapers** |
| | CHN01006 | 1.4 | Sitting: watching TV |
| | CHN01008 | 1.2 | Sitting: using mobile phone/**doing eye exercises** |
| | **CHN01010** | **1.4** | **Sitting: talking/greeting** |
| | **CHN01011** | **1.3** | **Sitting position: listening to music/radio** |
| | **CHN01012** | **1.5** | **Sitting: chess/mahjong** |
| | **CHN01013** | **1.7** | **Sitting: playing a musical instrument** |
| | **CHN01014** | **2.0** | **Standing: singing** |
| Walking | CHN02012 | 4.7 | Walking: brisk walking |
| | CHN02013 | 2.5 | Walking: slow frequency, 100 steps/min |
| | CHN02014 | 2.9 | Walking: natural walking |
| | CHN02015 | 4.2 | Walking: optimal speed, 4.0~6.4 km/h |
| Family Activities | **CHN04008** | **2.5** | **Child/pet care** |
| Fitness Exercise | CHN05003 | 5.4 | Square dancing |
| | **CHN05066** | **5.4** | **Aerobics (low to medium intensity)** |
| | **CHN05067** | **3.3** | **Use of fitness equipment** |
| Running Sports | CHN07045 | 4.7 | Running: average |
| | CHN09016 | 7.4 | Badminton: average |
| Traditional Chinese Sports | CHN12001 | 3.1 | Eight Section Brocade |
| | CHN12007 | 2.6 | Taichi Sword: average |
| | CHN12017 | 3.8 | Taichi: average |
| | CHN12018 | 3.5 | Taichi softball |
| | CHN12022 | 3.4 | Chinese Martial Arts: average |

Note: The bolded parts of the table are the author's activities added based on the survey, and their MET values are assigned with respect to similar activities.

### *3.4. Study Analyses*

A confirmatory factor analysis (CFA) and structural equation modeling (SEM) were conducted to examine our hypotheses. The CFA assessed the correlation between the two variables to determine whether the factors and latent variables within the proposed hypotheses were related. Following Fornell and Larcker's suggestion [57], composite reliability (CR) and average variance extracted (AVE) were selected as indicators of a correlation. The CR value represents the internal consistency of the construct indicators, which was suggested to be greater than 0.6. The AVE value represents the latent variables' explanatory power towards the measured variables. Hair et al. indicated that the AVE value should be greater than 0.25 [58]. Following the CFA results, SEM was used to investigate the association between GSP, GSU, and self-rated health in older people, as depicted in Figure 2. The model fit was then modified and tested for stability using AMOS23.0 (IBM Crop., Armonk, NY, USA). After constructing the model, we interpreted the results and verified their accuracy using SPSS26.0 statistical software (IBM Crop., Armonk, NY, USA) and AMOS23.0. This study's goodness-of-fit values included the root mean square error of approximation (RMSEA), the comparative fit index (CFI), the parsimonious CFI (PCFI),

the normed fit index (NFI), the Tucker–Lewis index (TLI), and the normed chi-square ratio ($\chi^2$/df). Finally, the impact of the intervening factors was examined using the path coefficient. The adjusted model's indirect, total, and mediated effects were analyzed for statistical significance using bootstrapping.

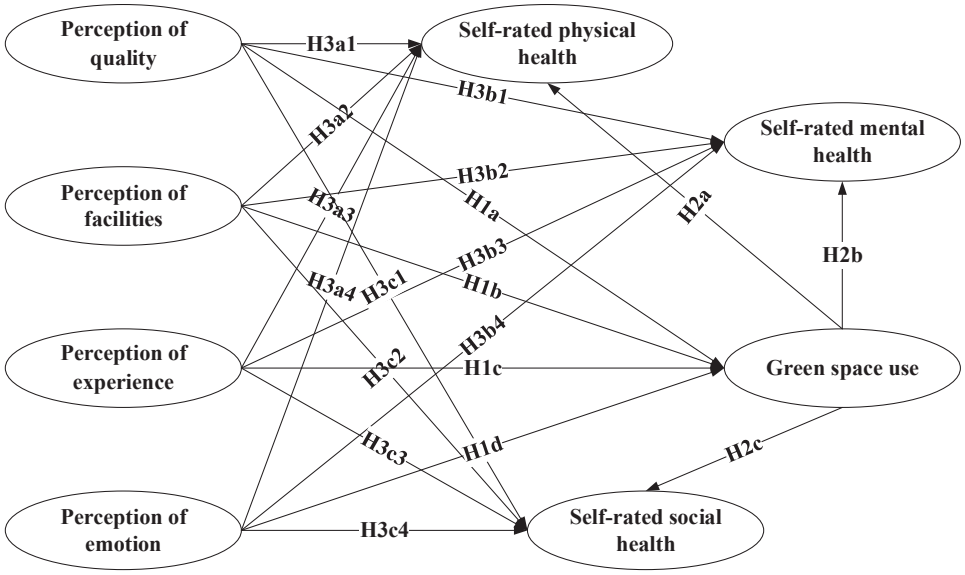



**Figure 2.** Hypothetical model.

## 4. Results

### *4.1. Analysis of Differences*

This study utilized Excel 2013 and SPSS to analyze its data. It examined the variations in the influence of green spaces on the health of older individuals of different ages, genders, and living styles. Furthermore, it examined the disparities in the perceptual ratings of various park environments, as presented in Table 3. The survey results indicate that, among the older adults interviewed, women generally rated their physical, psychological, and social health higher than men, which may be attributed to their higher life expectations, stronger health consciousness, and more proactive health behaviors. When comparing the health of older people by age group, those over 80 had the lowest physical, psychological, and social well-being levels. In contrast, those aged 71 to 80 had slightly higher levels. Their comparatively better physical health, greater social activity levels, and more adept psychological flexibility may contribute to this phenomenon.

**Table 3.** Differences in the impact of green spaces on the health of the elderly.

| Variables | Title | Mean (Standard Deviation) | | |
|---|---|---|---|---|
| | | Self-Rated Physical Health | Self-Rated Mental Health | Self-Rated Social Health |
| Gender | Male | 5.35 (1.19) | 5.23 (1.31) | 5.20 (1.37) |
| | Female | 5.46 (1.13) | 5.42 (1.24) | 5.36 (1.19) |
| Age | 60–70 | 5.39 (1.19) | 5.31 (1.28) | 5.33 (1.27) |
| | 71–80 | 5.46 (1.11) | 5.43 (1.23) | 5.34 (1.29) |
| | Above 80 | 5.31 (1.17) | 5.11 (1.34) | 4.93 (1.29) |
| Living style | Living with a partner | 5.40 (1.14) | 5.29 (1.29) | 5.32 (1.23) |
| | Living with three generations of family | 5.52 (1.22) | 5.47 (1.15) | 5.35 (1.28) |
| | Living with their children | 5.41 (1.16) | 5.34 (1.32) | 5.23 (1.31) |
| | Living alone | 4.95 (1.12) | 4.89 (1.47) | 4.85 (1.46) |

Regarding living arrangements, older people living in three-generation households had the highest health indices across all categories due to strong family support and

frequent social interactions; those living alone had the lowest health levels, owing primarily to social isolation and a lack of daily support. Elderly individuals living with a spouse or children showed no significant differences in these health metrics, generally maintaining higher levels. These findings highlight the considerable impact of family support and social interaction on the health of older adults.

Table 4 shows the differences in elderly respondents' perceptions of green spaces in different parks. West Lake Park received the highest overall average score for green space quality, suggesting that its green space is highly regarded and appreciated by elderly visitors. This further contributes to its reputation as a nationally recognized 3A tourist attraction. Regarding facilities, Zuohai Park and Jinshan Park received the highest average scores.

**Table 4.** Differences in elderly perceptions of various park green spaces.

| Investigated Area | Mean (Standard Deviation) | | | |
|---|---|---|---|---|
| | **Perception of Quality** | **Perception of Facilities** | **Perception of Experiences** | **Perception of Emotions** |
| West Lake Park | 5.38 (1.25) | 5.38 (1.27) | 5.40 (1.13) | 5.37 (1.32) |
| Zuohai Park | 5.21 (1.23) | 5.41 (1.12) | 5.31 (1.42) | 5.28 (1.17) |
| Minjiang Park | 5.21 (1.27) | 5.35 (1.26) | 5.43 (1.29) | 5.25 (1.38) |
| Jinshan Park | 5.28 (1.29) | 5.41 (1.23) | 5.57 (1.04) | 5.47 (1.20) |

According to the field surveys, these parks offer a wide variety of fitness facilities that are particularly suitable for elderly individuals' use. Regarding experience and emotional perception, Jinshan Park scored the highest, likely because it serves as a community park primarily catering to residents with fewer visiting tourists, fostering stronger emotional connections and better green space experiences for older adults.

### *4.2. Reliability and Validity Analyses*

An analysis of reliability and validity was performed on the data obtained from the questionnaire. The reliability of the survey results was tested using Cronbach's alpha coefficient, as indicated in Table 5. The alpha coefficient for the total scale was 0.954, the alpha coefficients for each subscale were above 0.90, and all CR values were >0.8. This indicates that each latent variable's observed variables were well designed and that the questionnaire was highly reliable. The validity tests of the questionnaire, using an exploratory factor analysis, revealed that the Kaiser–Meyer–Olkin (KMO) value for the total scale was 0.947, and those for each subscale were greater than 0.70. All the *p*-values from Bartlett's sphericity tests were <0.01, and all the AVE values were >0.7, indicating high convergent validity. The reliability and validity test results showed that the questionnaire was suitable for factor analysis.

**Table 5.** Confirmatory factor analysis.

| Factors | Observation Metrics | Standard Factor Loading | Cronbach's α | KMO | AVE | CR |
|---|---|---|---|---|---|---|
| Perception of quality | A1 Landscape aesthetics | 0.864 | 0.924 | 0.862 | 0.752 | 0.924 |
| | A2 Landscape richness | 0.866 | | | | |
| | A3 Environmental ecological degree | 0.885 | | | | |
| | A4 Degree of park maintenance | 0.854 | | | | |
| Perception of facilities | A5 Reasonable layout of leisure facilities | 0.866 | 0.943 | 0.934 | 0.736 | 0.944 |
| | A6 Night lighting perfection | 0.850 | | | | |
| | A7 Reasonable configuration of barrier-free facilities | 0.855 | | | | |
| | A8 Reasonable configuration of recreation and fitness facilities | 0.856 | | | | |
| | A9 The layout of the venue is reasonable | 0.874 | | | | |
| | A10 Suitability of venue scale | 0.845 | | | | |

**Table 5.** *Cont.*

| Factors | Observation Metrics | Standard Factor Loading | Cronbach's α | KMO | AVE | CR |
|---|---|---|---|---|---|---|
| Perception of experience | A11 Leisure and entertainment | 0.854 | 0.898 | 0.752 | 0.747 | 0.898 |
| | A12 Environmental comfort | 0.875 | | | | |
| | A13 Accessibility | 0.863 | | | | |
| Perception of emotion | A14 Sense of spatial belonging | 0.874 | 0.923 | 0.861 | 0.749 | 0.923 |
| | A15 Sense of spatial attachment | 0.861 | | | | |
| | A16 Sense of spatial familiarity | 0.854 | | | | |
| | A17 Sense of spatial security | 0.873 | | | | |
| Green space use | B1 Hours of green space activity per week | 0.897 | 0.911 | 0.757 | 0.775 | 0.912 |
| | B2 Frequency of green space visits per week | 0.874 | | | | |
| | B3 Total number of visits to green spaces per week | 0.869 | | | | |
| Self-rated physical health | C1 Good health in the last four weeks | 0.871 | 0.926 | 0.940 | 0.716 | 0.927 |
| | C2 In the past four weeks, physical health has made it difficult for you to do your job or other daily activities | 0.841 | | | | |
| | C3 Overall, you think your physical health is good | 0.836 | | | | |
| | C4 Here, you feel your body is relaxed | 0.827 | | | | |
| | C5 Here, you feel energized | 0.856 | | | | |
| Self-rated mental health | C6 Feeling relaxed | 0.876 | 0.951 | 0.906 | 0.765 | 0.951 |
| | C7 Feel calm and relaxed | 0.868 | | | | |
| | C8 Feeling energized | 0.885 | | | | |
| | C9 Feeling confident | 0.870 | | | | |
| | C10 Feeling awake and rested enough | 0.890 | | | | |
| | C11 Feeling that life is full of exciting things | 0.857 | | | | |
| Self-rated social health | C12 Where you get more opportunities to meet new people | 0.871 | 0.927 | 0.863 | 0.760 | 0.927 |
| | C13 Where you can get along with people in your neighborhood and solve problems together | 0.887 | | | | |
| | C14 Where you get more attention | 0.878 | | | | |
| | C15 Where you feel you can trust most of the people you interact with | 0.851 | | | | |

### *4.3. Hypothesis Model Analysis*

The model's goodness-of-fit results were as follows: $\chi^2/df = 1.124 < 5$; GFI = 0.938 > 0.8; AGFI = 0.927 > 0.8; RMSEA = 0.016 < 0.05; NFI = 0.962 > 0.9; TLI = 0.995 > 0.9; IFI = 0.996 > 0.8; CFI = 0.996 > 0.9; PGFI = 0.797 > 0.5; and PNFI = 0.865 > 0.5. These values indicated that

the theoretical model in this study fits the observed data well and can be subjected to path regression analysis.

The SEM results are shown in Figure 3, where the relationship between the individual measurement variables and the degree of influence of each measured indicator is indicated by the magnitude of their standardized path coefficients. These CR values or *p*-values can be used to assess the validity of the regression paths in each measurement model. The path coefficient is significant when CR > 1.96 or $p < 0.05$.

As shown in Table 6, the perception of the green space, including the perception of its quality (PQ), perception of its facilities (PF), perception of its experiences (PEX), and perception of emotions (PEM), exerted a significantly positive influence on GSU ($p < 0.005$). All hypotheses, H1a, H1b, H1c, and H1d, were confirmed. Out of all the factors, PF had the highest standardized path coefficient (0.260), suggesting that PF had the most substantial influence on place identity. It was followed by PQ, PEX, and PEM. GSU had a notably beneficial impact on physical health (PH), mental health (MH), and social health (SH) ($p < 0.005$). These illustrate the positive impact on physical, mental, and social health when older people use green spaces. Thus, H2a, H2b, and H2c were supported. Among the effects of perceived green spaces on physiological health, PF, PEX, and PEM significantly influenced physical health ($p < 0.005$). The PEM had the largest standardized path coefficient, indicating that PEM had the most significant impact on physical health, followed by PEX and PF. Furthermore, PQ had no significant effect on physical health ($p = 0.152$), and H3a2, H3a3, and H3a4 were supported. The four dimensions of GSP (PQ, PF, PEX, and PEM) had a significant positive effect on mental health ($p < 0.005$). As such, H3b1, H3b2, H3b3, and H3b4 were all supported. Their path coefficients were, in descending order, PEM (0.250) > PF (0.182) > PQ (0.142) > PEX (0.099). In terms of the effects of GSU on social health, PQ, PEX, and PEM had significant positive effects on physical health ($p < 0.005$). Their path coefficients were, in descending order, PEM (0.199) > PQ (0.157) > PEX (0.157). Furthermore, PF did not significantly impact social health statistically ($p = 0.077$). Thus, H3c1, H3c3, and H3c4 were supported. To summarize, how older individuals perceive green spaces can substantially impact their general subjective well-being and health. However, it is important to note that these perceptions may not always directly affect their physical health. On the other hand, GSU indirectly impacts the health of older individuals.

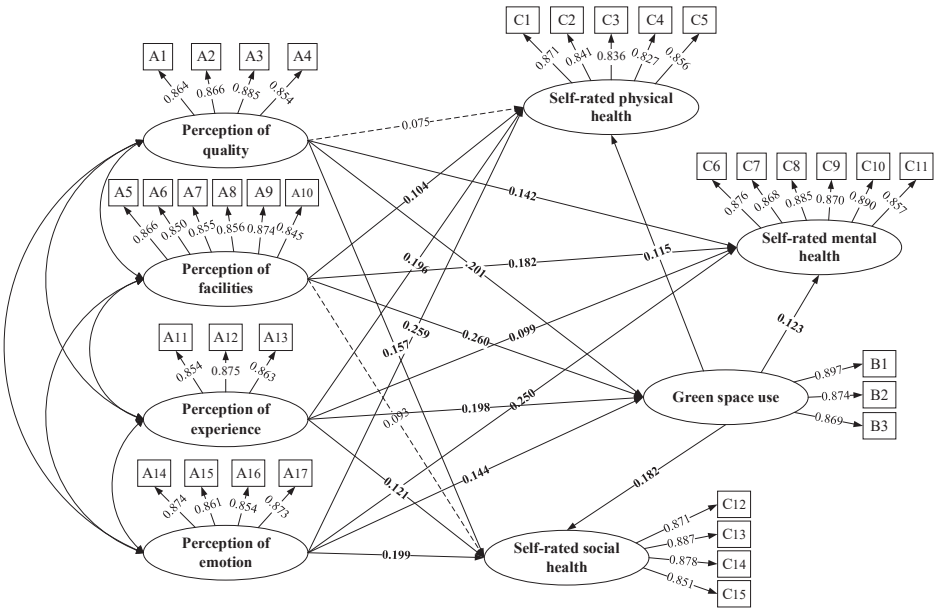



**Figure 3.** Standard estimates of the structural equation model path analysis.

**Table 6.** Tests for mediation effects.

| Hypothesis | Direction | *p* | Standardization Regression Coefficient | S.E. | CR. | Conclusion |
|---|---|---|---|---|---|---|
| H1a | PQ→GSU | *** | 0.201 | 0.056 | 4.001 | Supported |
| H1b | PF→GSU | *** | 0.260 | 0.059 | 5.203 | Supported |
| H1c | PEX→GSU | *** | 0.198 | 0.056 | 4.067 | Supported |
| H1d | PEM→GSU | 0.003 | 0.144 | 0.053 | 2.987 | Supported |
| H2a | GSU→PH | 0.032 | 0.115 | 0.045 | 2.150 | Supported |
| H2b | GSU→MH | 0.016 | 0.123 | 0.046 | 2.401 | Supported |
| H2c | GSU→SH | 0.018 | 0.182 | 0.055 | 2.375 | Supported |
| H3a1 | PQ→PH | 0.152 | 0.075 | 0.049 | 1.432 | Unsupported |
| H3a2 | PF→PH | 0.046 | 0.104 | 0.052 | 1.993 | Supported |
| H3a3 | PEX→PH | *** | 0.196 | 0.050 | 3.839 | Supported |
| H3a4 | PEM→PH | *** | 0.259 | 0.047 | 5.103 | Supported |
| H3b1 | PQ→MH | 0.004 | 0.142 | 0.050 | 2.846 | Supported |
| H3b2 | PF→MH | *** | 0.182 | 0.053 | 3.612 | Supported |
| H3b3 | PEX→MH | 0.042 | 0.099 | 0.051 | 2.038 | Supported |
| H3b4 | PEM→MH | *** | 0.250 | 0.048 | 5.155 | Supported |

**Table 6.** *Cont.*

| Hypothesis | Direction | *p* | Standardization Regression Coefficient | S.E. | CR. | Conclusion |
|---|---|---|---|---|---|---|
| H3c1 | PQ→SH | 0.003 | 0.157 | 0.054 | 2.999 | Supported |
| H3c2 | PF→SH | 0.077 | 0.093 | 0.057 | 1.769 | Unsupported |
| H3c3 | PEX→SH | 0.018 | 0.121 | 0.055 | 2.375 | Supported |
| H3c4 | PEM→SH | *** | 0.199 | 0.052 | 3.946 | Supported |

Note: *** indicates 1% significance levels.

Mediating effects were further analyzed to explore the pathways through which older people's GSPs influence their GSU and multidimensional health. As shown in Table 7, the test of the mediation effects showed that, in H3a2, H3a3, and H3a4, GSU mediated the relationship between perception (PF, PEX, and PEM) and physical health, supporting H4a. Then, in H3b1, H3b2, H3b3, and H3b4, GSU mediated the relationship between perception (PQ, PF, PEX, and PEM) and mental health, supporting H4b. Furthermore, in H3c1, H3c3, and H3c4, GSU mediated the relationship between perception (PQ, PF, PEX, and PEM) and social health, supporting H4c.

**Table 7.** Tests for intermediary effects.

| Hypothesis | Direction | *p* | Direct Effect | Indirect Effect | Total Effect |
|---|---|---|---|---|---|
| H1a | PQ→GSU | *** | 0.201 | 0.000 | 0.201 |
| H1b | PF→GSU | *** | 0.260 | 0.000 | 0.260 |
| H1c | PEX→GSU | *** | 0.198 | 0.000 | 0.198 |
| H1d | PEM→GSU | 0.003 | 0.144 | 0.000 | 0.144 |
| H2a | GSU→PH | 0.032 | 0.115 | 0.000 | 0.115 |
| H2b | GSU→MH | 0.016 | 0.123 | 0.000 | 0.123 |
| H2c | GSU→SH | 0.018 | 0.182 | 0.000 | 0.182 |
| H3a1 | PQ→PH | 0.152 | 0.075 | 0.023 | 0.098 |
| H3a2 | PF→PH | 0.046 | 0.104 | 0.030 | 0.134 |
| H3a3 | PEX→PH | *** | 0.196 | 0.023 | 0.219 |
| H3a4 | PEM→PH | *** | 0.259 | 0.017 | 0.275 |
| H3b1 | PQ→MH | 0.004 | 0.142 | 0.025 | 0.167 |
| H3b2 | PF→MH | *** | 0.182 | 0.032 | 0.213 |
| H3b3 | PEX→MH | 0.042 | 0.099 | 0.024 | 0.123 |
| H3b4 | PEM→MH | *** | 0.250 | 0.018 | 0.267 |
| H3c1 | PQ→SH | 0.003 | 0.157 | 0.037 | 0.194 |
| H3c2 | PF→SH | 0.077 | 0.093 | 0.047 | 0.140 |
| H3c3 | PEX→SH | 0.018 | 0.121 | 0.036 | 0.157 |
| H3c4 | PEM→SH | *** | 0.199 | 0.026 | 0.225 |

Note: Test results of direct, indirect, and total effects of standardization between latent variables. *** indicates 1% significance levels.

## 5. Discussion

This study found a significant positive association between older adults' perceptions of green spaces, including their quality, facilities, experiences, and emotions, and their use. This supported previous findings that linked green space utilization to improved physical, psychological, and social health among older people. Interestingly, the indirect effects of GSU were apparent, even though some of the direct impacts of GSP on health were minimal. This shows that green spaces' qualities and features, as well as the experiences and emotional connections they produce, are vital in supporting older people's multidimensional health.

### *5.1. Green Space Perception and Green Space Use by Older People*

This study discovered that the GSU and perceptions of older persons impacted their multidimensional health. Furthermore, there was a strong positive association between older adults' use of green space and their perceptions of the space's quality, amenities, experiences, and emotions. This supports earlier research and emphasizes the value of GSP in encouraging older persons to engage in active outdoor activities [26,27]. When the standardized path coefficients of the four dimensions of the perceptions of green spaces were compared, facility perceptions played the most crucial role in promoting GSU. This reveals the pivotal role of good infrastructure, such as well-laid-out activity spaces, reasonable accessibility, and reasonable recreational and fitness facilities, in attracting older people to green spaces. On-site interviews revealed that age-appropriate amenities, such as benches, shade, and restrooms, significantly enhanced older adults' use of green spaces, aligning with the findings that such facilities increase visitation frequency [15,26].

Moreover, when older adults perceive green spaces to be highly environmentally friendly and well-maintained, they are more likely to spend time using them [13]. This shows that the frequency and duration of GSU are often positively connected with assessments of the quality of green spaces. The way that a green space is used is also influenced by visitors' perceptions and overall experience in the park, including their recreation and its accessibility. This is consistent with previous studies showing that older people's perceptions of security and attachment to their surroundings were favorably correlated with their social, psychological, and physical health [59]. These findings provide evidence that GSP has a unifying impact on the GSU of older individuals. Therefore, to encourage

older persons to utilize green spaces, it is advised that future park landscape design and green space management prioritize raising the quality of green spaces, upgrading facilities, enriching the overall experience of green spaces, and strengthening emotional connections.

### *5.2. Green Space Use and Multidimensional Health in Older Adults*

The present investigation revealed an excellent correlation between GSU and older persons' physical, mental, and social health, which aligns with previous research findings. Urban parks provide areas for social contact and physical movement, which is especially beneficial for vulnerable populations [60]. It was found that GSU has the greatest effect on social health, followed by mental health, and there was a positive correlation with physical health. Engaging in activities in green spaces has a substantial positive impact on social well-being. These activities provide opportunities for social interaction, which aligns with the research conducted by Whear et al. Their findings suggest that participating in group activities in green spaces helps establish new social connections and alleviates feelings of loneliness [61].

Furthermore, the calming environment of green spaces aids in mitigating stress, anxiety, and depression among older people, supporting existing studies [62,63]. Under lockdowns, a lack of access to these spaces intensified depression and anxiety symptoms, highlighting the mood-enhancing effects of natural landscapes [64]. Parks and urban green spaces provide a space for health-promoting behaviors, including physical activity [65] and social interaction [16], and older people's activities in green spaces positively impact their physical, mental, and social health. Interviews with study participants indicated that the observed little immediate impact on their physical health may be because some participants started these activities recently. Encouraging older people to use green areas can improve their health.

### *5.3. Green Space Perception and Multidimensional Health in Older Adults*

The GSPs of older people have shown some positive relationships with their physical, mental, and social well-being in this study, which agreed with previous studies [34,66]. Green spaces are vital natural environments facilitating physical activity, mental relaxation, and the emotional well-being of older people.

This study had an indirect effect; however, the direct relationship between quality perception and physiological health was not very strong. This finding, when combined with the interview results, might indicate that the physiological health of older individuals is not directly impacted by their perceptions of a green space's quality. However, the use of green spaces can indirectly promote it. This research emphasizes the direct correlation between the experiences and emotions of older individuals regarding green spaces and their propensity to revisit these areas to enhance their health. This encompasses their perception of safety and the suitability of the leisure and fitness facilities.

Moreover, these findings underscore the mediating role of facilities, experiences, and emotional perceptions in the effect on older adults' physical health and support the idea that positive perceptions of green spaces can increase outdoor activities. Regularly active older adults in green spaces exhibit better physical function and lower chronic disease rates [67]. The pathway by which GSPs influenced the emotional state and mental health of older individuals was as follows: quality perception, experience perception, emotion perception, and facility perception all had direct and indirect positive effects on the mental health of older individuals. This evidence substantiates the claim that green spaces have the potential to improve mental health and emotional well-being, as well as alleviate stress, anxiety, and depression; thus, this supports the notion that green spaces enhance life satisfaction [68]. Furthermore, while direct effects of facility perceptions on social health were not observed, indirect benefits, through increased GSU and social interaction, were noted, suggesting that the aesthetic and maintenance level of parks and a sense of belonging foster social engagement, which reduces loneliness and social isolation. Perceived quality, experience, and emotion all had favorable effects on the social health of older individuals.

This study confirms that the perceived quality, knowledge, and emotion of green spaces mediate the physical health of older individuals. This is consistent with existing research showing that the aesthetics [69] and maintenance of urban green spaces [28] encourage older adults to socialize and participate in outdoor activities, thereby reducing loneliness and social isolation.

Notably, the path coefficients we obtained indicated that the direct effects of green space quality on physical, mental, and social health were the most significant among the many impacts of green space quality on multidimensional health. These findings indicate that it is crucial to prioritize efforts to improve older people's emotional experiences of green spaces, such as their feelings of belonging, familiarity, connection, and security. This is crucial for enhancing their physical, mental, and social well-being.

### *5.4. Limitations of the Study*

Although the findings of this study are consistent with the existing literature overall, there are some limitations. In terms of sample selection, this study used random sampling for the questionnaire survey, resulting in more than half of the respondents being between 60 and 70 years of age. Furthermore, various conditions may be connected to poor health in older adults. Not all of them have been covered in this study; only a few related to GSP and GSU activities have been discussed. Lastly, this study did not include objective measurements; instead, it used questionnaires to subjectively test participants' self-reported GSP, GSU, and health conditions.

## 6. Conclusions

Designing and maintaining urban green spaces, particularly in places with a high rate of aging, requires an understanding of how older people view and use these spaces. This study investigated the factors impacting the GSPs, GSU, and self-reported multidimensional health of older persons in addition to developing indicators to assess their GSPs. This study presents a novel comparison of several pathways in a single model. The current model uniquely compares multiple pathways, identifying emotional perception as the most influential GSP factor on GSU and health. We found that, overall, GSP and GSU were positively correlated with better health outcomes. However, no significant links were observed between green space quality, physical health, facilities, and social health.

Furthermore, GSU notably enhances social health. These findings suggest that enhancing green space quality, facilities, and emotional experiences can significantly benefit older people's health. To better serve the elderly, future urban park developments should improve facilities like benches, pathways, and pavilions to meet elderly needs and enhance convenience. Given the positive impact of green space usage on social health, spaces should be designed to encourage social interaction among older adults, and activities like health exercises and tai chi should be regularly organized. Moreover, implementing a feedback mechanism to collect continuous input from older users can enhance green spaces' design and improve their health. Future research must consider and account for the confounding variable of elderly individuals' overall health, including chronic diseases and physical limitations. In addition, using GPS trackers and electronic devices to document activities and assess physiological markers before and following trips to green spaces could improve our data-gathering techniques and deepen our comprehension of their health impacts.

**Author Contributions:** Data curation, Y.W. and W.Z.; Investigation, Y.W., H.Z. and Z.Y.; Methodology, Y.W., W.Z., H.Z. and Z.Y.; Writing—original draft, Y.W.; Writing—review and editing, Q.L. and S.L.; Supervision, Q.L.; Funding acquisition, Q.L. and S.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors gratefully acknowledge the financial support from The First Stage of Support for the First batch of Mass Entrepreneurship and Innovation Talents in Fujian Province under grant K8615001A, Fujian Provincial Department of Education under grant No. JAT220220, and Fujian Provincial Department of Science and Technology under grant 2023J05193.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author due to privacy.

**Conflicts of Interest:** Author Zhao Yan was employed by the company Fuzhou Minhou County Shangyi Education Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## References

1. UN Report Calls for Re-Thinking Social Protection as the World Ages | UN News [EB/OL]. (2023-01-12). Available online: https://news.un.org/en/story/2023/01/1132392 (accessed on 9 April 2024).
2. Huang, B.; Huang, C.; Feng, Z.; Pearce, J.R.; Zhao, H.; Pan, Z.; Liu, Y. Association between residential greenness and general health among older adults in rural and urban areas in China—ScienceDirect. *Urban For. Urban Green.* **2020**, *59*, 126907. [CrossRef]
3. Jiang, H.; Liu, Z. Community home elderly care services, multidimensional health and social participation of chronically ill elderly—Empirical analysis based on propensity score matching and multiple mediation analysis. *Front. Public Health* **2023**, *11*, 1121909. [CrossRef]
4. Enssle, F.; Kabisch, N. Urban green spaces for the social interaction, health and well-being of older people—An integrated view of urban ecosystem services and socio-environmental justice. *Environ. Sci. Policy* **2020**, *109*, 36–44. [CrossRef]
5. Egger, G.; Dixon, J. Beyond obesity and lifestyle: A review of 21st century chronic disease determinants. *Biomed. Res. Int.* **2014**, *2014*, 731685. [CrossRef] [PubMed]
6. Kaplan, S. The restorative benefits of nature: Toward an integrative framework. *J. Environ. Psychol.* **1995**, *15*, 169–182. [CrossRef]
7. Ali, M.d.J.; Rahaman, M.; Hossain, S.k.I. Urban green spaces for elderly human health: A planning model for healthy city living. *Land Use Policy* **2022**, *114*, 105970. [CrossRef]
8. Zhou, R.; Zheng, Y.-J.; Yun, J.-Y.; Wang, H.-M. The Effects of Urban Green Space on Depressive Symptoms of Mid-Aged and Elderly Urban Residents in China: Evidence from the China Health and Retirement Longitudinal Study. *Int. J. Environ. Res. Public Health* **2022**, *19*, 717. [CrossRef] [PubMed]
9. de Jong, K.; Albin, M.; Skärbäck, E.; Grahn, P.; Björk, J. Perceived green qualities were associated with neighborhood satisfaction, physical activity, and general health: Results from a cross-sectional study in suburban and rural Scania, southern Sweden. *Health Place* **2012**, *18*, 1374–1380. [CrossRef] [PubMed]
10. Bjork, J.; Albin, M.; Grahn, P.; Jacobsson, H.; Ardo, J.; Wadbro, J.; Ostergren, P.-O.; Skarback, E. Recreational values of the natural environment in relation to neighbourhood satisfaction, physical activity, obesity and well-being. *J. Epidemiol. Community Health* **2008**, *62*, e2. [CrossRef]
11. Ma, Y.; Brindley, P.; Lange, E. The Influence of Socio-Demographic Factors on Preference and Park Usage in Guangzhou, China. *Land* **2022**, *11*, 1219. [CrossRef]
12. Park, K. *Park and Neighborhood Attributes Associated with Park Use: An Observational Study Using Unmanned Aerial Vehicles*; SAGE Publications: Los Angeles, CA, USA, 2020.
13. Sugiyama, T.; Thompson, C.W. Older people's health, outdoor activity and supportiveness of neighbourhood environments. *Landsc. Urban Plan.* **2007**, *83*, 168–175. [CrossRef]
14. Sadeghian, M.M. *The Health Benefits of Urban Green Spaces, a Literature Review*; IJARIIE: New Delhi, India, 2018.
15. Gong, Y.; Gallacher, J.; Palmer, S.; Fone, D. Neighbourhood green space, physical function and participation in physical activities among elderly men: The Caerphilly Prospective study. *Int. J. Behav. Nutr. Phys. Act.* **2014**, *11*, 40. [CrossRef] [PubMed]
16. Maas, J.; Van Dillen, S.M.; Verheij, R.A.; Groenewegen, P.P. Social contacts as a possible mechanism behind the relation between green space and health. *Health Place* **2009**, *15*, 586–595. [CrossRef] [PubMed]
17. Lau, K.K.L. Usage and perception of urban green space of older adults in the high-density city of Hong Kong. *Urban For. Urban Green.* **2021**, *64*, 127251. [CrossRef]
18. Tan, Z.; Lau, K.K.L.; Roberts, A.C.; Chao, S.T.-Y.; Ng, E. Designing Urban Green Spaces for Older Adults in Asian Cities. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4423. [CrossRef] [PubMed]
19. Thompson, C.W.; Aspinall, P.; Bell, S.; Findlay, C. "It Gets You Away from Everyday Life": Local Woodlands and Community Use—What Makes a Difference? *Landsc. Res.* **2005**, *30*, 109–146. [CrossRef]
20. Bell, S.; Thompson, C.W.; Travlou, P. Contested views of freedom and control: Children, teenagers and urban fringe woodlands in Central Scotland. *Urban For. Urban Green.* **2003**, *2*, 87–100. [CrossRef]
21. Finlay, J.; Franke, T.; McKay, H.; Sims-Gould, J. Therapeutic landscapes and well-being in later life: Impacts of blue and green spaces for older adults. *Health Place* **2015**, *34*, 97–106. [CrossRef] [PubMed]
22. Thompson, C.W.; Roe, J.; Aspinall, P.; Mitchell, R.; Clow, A.; Miller, D. More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. *Landsc. Urban Plan.* **2012**, *105*, 221–229. [CrossRef]
23. Jim, C.Y.; Shan, X. Socioeconomic effect on perception of urban green spaces in Guangzhou, China. *Cities* **2013**, *31*, 123–131. [CrossRef]
24. Schipperijn, J.; Bentsen, P.; Troelsen, J.; Toftager, M.; Stigsdotter, U.K. Associations between physical activity and characteristics of urban green space. *Urban For. Urban Green.* **2013**, *12*, 109–116. [CrossRef]

25. Miralles-Guasch, C.; Dopico, J.; Delclòs-Alió, X.; Knobel, P.; Marquet, O.; Maneja-Zaragoza, R.; Schipperijn, J.; Vich, G. Natural Landscape, Infrastructure, and Health: The Physical Activity Implications of Urban Green Space Composition among the Elderly. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3986. [CrossRef] [PubMed]
26. Coles, R.W.; Bussey, S.C. Urban forest landscapes in the UK—Progressing the social agenda. *Landsc. Urban Plan.* **2000**, *52*, 181–188. [CrossRef]
27. Rodiek, S.D.; Fried, J.T. Access to the outdoors: Using photographic comparison to assess preferences of assisted living residents. *Landsc. Urban Plan.* **2005**, *73*, 184–199. [CrossRef]
28. Kweon, B.S.; Sullivan, W.C.; Wiley, A.R. Green Common Spaces and the Social Integration of Inner-City Older Adults. *Environ. Behav.* **1998**, *30*, 832–858. [CrossRef]
29. Cohen, D.A.; Marsh, T.; Williamson, S.; Derose, K.P.; Martinez, H.; Setodji, C.; McKenzie, T.L. Parks and physical activity: Why are some parks used more than others? *Prev. Med.* **2010**, *50*, S9–S12. [CrossRef] [PubMed]
30. Mitchell, R.; Popham, F. Effect of exposure to natural environment on health inequalities: An observational population study. *Lancet* **2008**, *372*, 1655–1660. [CrossRef] [PubMed]
31. Lee, I.M.; Paffenbarger, R.S., Jr. Associations of Light, Moderate, and Vigorous Intensity Physical Activity with Longevity: The Harvard Alumni Health Study. *Am. J. Epidemiol.* **2000**, *151*, 293–299. [CrossRef] [PubMed]
32. Twohig-Bennett, C.; Jones, A. The health benefits of the great outdoors: A systematic review and meta-analysis of greenspace exposure and health outcomes. *Environ. Res.* **2018**, *166*, 628–637. [CrossRef]
33. Roe, J.J.; Thompson, C.W.; Aspinall, P.A.; Brewer, M.J.; Duff, E.I.; Miller, D.; Mitchell, R.; Clow, A. Green Space and Stress: Evidence from Cortisol Measures in Deprived Urban Communities. *Int. J. Environ. Res. Public Health* **2013**, *10*, 4086–4103. [CrossRef]
34. Gascon, M.; Triguero-Mas, M.; Martínez, D.; Dadvand, P.; Forns, J.; Plasència, A.; Nieuwenhuijsen, M.J. Mental Health Benefits of Long-Term Exposure to Residential Green and Blue Spaces: A Systematic Review. *Int. J. Environ. Res. Public Health* **2015**, *12*, 4354–4379. [CrossRef] [PubMed]
35. Wood, C.J.; Pretty, J.; Griffin, M. A case–control study of the health and well-being benefits of allotment gardening. *J. Public Health* **2016**, *38*, e336–e344. [CrossRef] [PubMed]
36. Beyer, K.M.M.; Kaltenbach, A.; Szabo, A.; Bogar, S.; Nieto, F.J.; Malecki, K.M. Exposure to Neighborhood Green Space and Mental Health: Evidence from the Survey of the Health of Wisconsin. *Int. J. Environ. Res. Public Health* **2014**, *11*, 3453. [CrossRef] [PubMed]
37. Soga, M.; Gaston, K.J.; Yamaura, Y. Gardening is beneficial for health: A meta-analysis. *Prev. Med. Rep.* **2017**, *5*, 92–99. [CrossRef] [PubMed]
38. Dadvand, P.; Bartoll, X.; Basagaña, X.; Dalmau-Bueno, A.; Martinez, D.; Ambros, A.; Cirach, M.; Triguero-Mas, M.; Gascon, M.; Borrell, C.; et al. Green spaces and General Health: Roles of mental health status, social support, and physical activity. *Environ. Int.* **2016**, *91*, 161–167. [CrossRef] [PubMed]
39. Bagozzi, R.P. The Self-Regulation of Attitudes, Intentions, and Behavior. *Soc. Psychol. Q.* **1992**, *55*, 178–204. [CrossRef]
40. Zhang, L.; Tan, P.Y.; Diehl, J.A. A conceptual framework for studying urban green spaces effects on health. *J. Urban Ecol.* **2017**, *3*, jux015. [CrossRef]
41. Javadi, R.; Nasrollahi, N. Urban green space and health: The role of thermal comfort on the health benefits from the urban green space; a review study. *Build. Environ.* **2021**, *202*, 108039. [CrossRef]
42. Dong, Y.; Li, Z.; Dong, W. Relationship Between Green Space Perception of Communities and Residents' Stress Level: A Case Study of 12 Communities in Harbin. *Landsc. Archit.* **2020**, *27*, 88–93. (In Chinese)
43. Hedblom, M.; Gunnarsson, B.; Iravani, B.; Knez, I.; Schaefer, M.; Thorsson, P.; Lundström, J.N. Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Sci. Rep.* **2019**, *9*, 10113. [CrossRef]
44. Liu, Y.; Zhao, B.; Cheng, Y.; Zhao, T.; Zhang, A.; Cheng, S.; Zhang, J. Does the quality of street greenspace matter? Examining the associations between multiple greenspace exposures and chronic health conditions of urban residents in a rapidly urbanizing Chinese city. *Environ. Res.* **2023**, *222*, 115344. [CrossRef]
45. Wang, R.; Feng, Z.; Pearce, J.; Liu, Y.; Dong, G. Are greenspace quantity and quality associated with mental health through different mechanisms in Guangzhou, China: A comparison study using street view data. *Environ. Pollut.* **2021**, *290*, 117976. [CrossRef] [PubMed]
46. Yessoufou, K.; Sithole, M.; Elansary, H.O. Effects of urban green spaces on human perceived health improvements: Provision of green spaces is not enough but how people use them matters. *PLoS ONE* **2020**, *15*, e0239314. [CrossRef]
47. Huang, W.-Z.; Yang, B.-Y.; Yu, H.-Y.; Bloom, M.S.; Markevych, I.; Heinrich, J.; Knibbs, L.D.; Leskinen, A.; Dharmage, S.C.; Jalaludin, B.; et al. Association between community greenness and obesity in urban-dwelling Chinese adults. *Sci. Total Environ.* **2019**, *702*, 135040. [CrossRef]
48. Esther, H.K.Y.; Winky, K.O.H.; Edwin, H.W.C. Elderly satisfaction with planning and design of public parks in high density old districts: An ordered logit model. *Landsc. Urban Plan.* **2017**, *165*, 39–53. [CrossRef]
49. Lu, S.; Shu, P.; Wang, L. Paths and Effects of Residential Green Space's Restorative Characteristics on Older Adults' Mental Health Promotion. *S. Archit.* **2023**, 11–19. (In Chinese) [CrossRef]
50. Leslie, E.; Cerin, E. Are perceptions of the local environment related to neighbourhood satisfaction and mental health in adults? *Prev. Med.* **2008**, *47*, 273–278. [CrossRef]

51. Akpinar, A. How is quality of urban green spaces associated with physical activity and health? *Urban For. Urban Green.* **2016**, *16*, 76–83. [CrossRef]
52. Joseph, A.; Zimring, C.; Harris-Kojetin, L.; Kiefer, K. Presence and Visibility of Outdoor and Indoor Physical Activity Features and Participation in Physical Activity Among Older Adults in Retirement Communities. *J. Hous. Elder.* **2006**, *19*, 141–165. [CrossRef]
53. Jenkinson, C.; Layte, R. Development and Testing of the UK SF-12. *J. Health Serv. Res. Policy* **1997**, *2*, 14–18. [CrossRef]
54. Zhang, L.; Zhou, S.; Kwan, M.P. A comparative analysis of the impacts of objective versus subjective neighborhood environment on physical, mental, and social health. *Health Place* **2019**, *59*, 102170. [CrossRef] [PubMed]
55. Huang, W.; Lin, G. The concept, benefit and influencing factors of Urban Green Space Social Health. *Chin. Landsc. Archit.* **2023**, 77–82. (In Chinese) [CrossRef]
56. Qiu, J.; Yang, J.; Lu, M.; Chen, Y. Compilation of Physical Activities of Healthy Chinese Adults: Reference Values for Energy Expenditure. *Chin. J. Sports Med.* **2022**, *41*, 335–349. (In Chinese) [CrossRef]
57. Bagozzi, R.P. Evaluating Structural Equation Models with Unobservable Variables and Measurement Error: A Comment. *J. Mark. Res.* **1981**, *18*, 375–381. [CrossRef]
58. Hair, J.F.; Black, W.C.; Babin, B.J.; Anderson, R.E. *Multivariate Data Analysis: A Global Perspective*; Pearson: Hong Kong, China, 2014.
59. Lak, A.; Khodakarim, S.; Myint, P.K.; Baradaran, H.R. The influencing factors of elder-friendly public open spaces promoting older adults' health in deprived urban neighborhoods: Partial Least Square Structural Equation Modeling approach. *Front. Public Health* **2023**, *11*, 1143289. [CrossRef]
60. Kabisch, N.; Kraemer, R. Physical activity patterns in two differently characterized urban parks under conditions of summer heat. *Environ. Sci. Policy* **2020**, *107*, 56–65. [CrossRef]
61. Whear, R.; Coon, J.T.; Bethel, A.; Abbott, R.; Stein, K.; Garside, R. What Is the Impact of Using Outdoor Spaces Such as Gardens on the Physical and Mental Well-Being of Those with Dementia? A Systematic Review of Quantitative and Qualitative Evidence. *J. Am. Med. Dir. Assoc.* **2014**, *15*, 697–705. [CrossRef] [PubMed]
62. Huang, Y.; Yuan, X. Smellscape as a healing factor in institutional gardens to enhance health and well-being for older people with dementia: A scoping review. *J. Clin. Nurs.* **2024**, *33*, 454–468. [CrossRef] [PubMed]
63. Collins, R.; Owen, S.; Opdebeeck, C.; Ledingham, K.; Connell, J.; Quinn, C.; Page, S.; Clare, L. Provision of Outdoor Nature-Based Activity for Older People with Cognitive Impairment: A Scoping Review from the ENLIVEN Project. *Health Soc. Care Community* **2023**, *2023*, e4574072. [CrossRef]
64. Pouso, S.; Borja; Fleming, L.E.; Gómez-Baggethun, E.; White, M.P.; Uyarra, M.C. Contact with blue-green spaces during the COVID-19 pandemic lockdown beneficial for mental health. *Sci. Total Environ.* **2021**, *756*, 143984. [CrossRef]
65. Sallis, J.F.; Cerin, E.; Conway, T.L.; Adams, M.A.; Frank, L.D.; Pratt, M.; Salvo, D.; Schipperijn, J.; Smith, G.; Cain, K.L.; et al. Physical activity in relation to urban environments in 14 cities worldwide: A cross-sectional study. *Lancet* **2016**, *387*, 2207–2217. [CrossRef] [PubMed]
66. Shu, S.; Meng, L.; Piao, X.; Geng, X.; Tang, J. Effects of Audio–Visual Interaction on Physio-Psychological Recovery of Older Adults in Residential Public Space. *Forests* **2024**, *15*, 266. [CrossRef]
67. White, M.P.; Wheeler, B.W.; Herbert, S.; Alcock, I.; Depledge, M.H. Coastal proximity and physical activity: Is the coast an under-appreciated public health resource? *Prev. Med. Int. J. Devoted Pract. Theory* **2014**, *69*, 135–140. [CrossRef] [PubMed]

68. White, M.P.; Alcock, I.; Grellier, J.; Wheeler, B.W.; Hartig, T.; Warber, S.L.; Bone, A.; Depledge, M.H.; Fleming, L.E. Spending at least 120 min a week in nature is associated with good health and well-being. *Sci. Rep.* **2019**, *9*, 7730. [CrossRef]
69. Coon, J.T.; Boddy, K.; Stein, K.; Whear, R.; Barton, J.; Depledge, M.H. Does participating in physical activity in outdoor natural environments have a greater effect on physical and mental well-being than physical activity indoors? A systematic review. *Br. J. Soc. Med.* **2011**, *65* (Suppl. 2), A38.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# An Evaluation Model of Urban Green Space Based on Residents' Physical Activity

**Tian Dong, Churan Feng *, Bangguo Yue and Zhengdong Zhang**

School of Architecture and Art, Central South University, Changsha 410075, China; dongtian@csu.edu.cn (T.D.); 8214200405@csu.edu.cn (B.Y.); 8214200118@csu.edu.cn (Z.Z.)
* Correspondence: 8214200111@csu.edu.cn

**Abstract:** Urban green spaces (UGSs) possess a status in improving public health; thus, it is crucial to emphasize the evaluation of UGSs in terms of residents' physical activity (PA). This study utilizes the semantic segmentation method and Geographic Information System tools to quantify the key values of UGSs, including aesthetic and attractions, natural world experience, nature conservation, encouraging physical activity, cultural value, and social value, which are set as the evaluation indexes to investigate their impacts on residents' PA based on the six UGSs in Changsha city, Hunan Province, China. The PA-oriented UGS evaluation model is realized through the index optimal combination weights obtained by the Improved Combination Weighting Method of Game Theory, combining the subjective and objective weights from the Uncertainty Analytic Hierarchy Process method and Entropy Weight Method, respectively. By collecting and analyzing the exercise data of residents, we can accurately assess the level of residents' PA and frequency within various UGSs. The proposed model herein has a positive significance for evaluating the value of public green space in residents' PA in Changsha city and provides a reference for the construction of an urban green space evaluation model from multiple perspectives in the future.

**Keywords:** urban green space; physical activity; evaluation model; GIS; semantic segmentation; improved combined weighting method of game theory (ICWGT)

**Citation:** Dong, T.; Feng, C.; Yue, B.; Zhang, Z. An Evaluation Model of Urban Green Space Based on Residents' Physical Activity. *Sustainability* **2024**, *16*, 4220. https://doi.org/10.3390/su16104220

Academic Editors: Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Baojie He and Shi Cheng

Received: 28 April 2024
Revised: 14 May 2024
Accepted: 15 May 2024
Published: 17 May 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

It is generally acknowledged that urban green space (UGS) is an available resource, which usually includes parks, gardens, street greening, natural woodland, etc. Urban green space not only provides urban residents with places for leisure, entertainment, exercise, social interaction, and various collective cultural activities but also plays an important positive role in residents' physical health [1–3]. According to the World Health Organization (WHO), the development of green spaces and other nature-based construction solutions can improve the quality of the urban environment, leading to the promotion of sustainable lifestyles and the enhancement of the physical and mental health of urban residents, as well as bringing many other benefits [4]. People who visit the parks benefit from UGS to obtain higher sociological capability in cognitive, emotional, and psychological aspects, significantly reducing stress and mental fatigue while enhancing attention and memory ability [5]. Relevant studies have shown that urban green space can optimize the human living environment and life quality. Some scholars found that there was a significant positive correlation between the time residents spent in green space and their physical and mental health [6]. According to demographic data, outdoor daily physical activity (PA) has a significant effect on the physical health of residents, which can also prevent mental illness to a certain extent [7,8]. In 2023, the Australian Sports Medicine Association and the Australian Psychological Society put forward guidelines on how to maximize the physical and mental benefits of physical activity. It was clearly stated that some physical activity should be carried out outdoors in a pleasant natural environment [9]. From this

perspective, urban green spaces (UGSs) are the ideal places offering a safe, accessible, and attractive environment to encourage urban residents to engage in physical activity. Meanwhile, UGSs which provide necessary services also could increase the time spent on outdoor activities, which in turn helps to reduce the occurrence of chronic diseases and mortality among participants [10]. Overall, the quality of UGSs reflects the attractiveness to residents living nearby, which is related to the frequency of visiting green spaces and is a key factor affecting the physical and mental health of urban residents [11]. Hence, objective and reasonable evaluation can contribute to focusing our understanding of UGSs, enabling the implementation of corresponding measures to improve the quality of the urban environment, thereby effectively enhancing the well-being of urban residents.

The accelerated process of urbanization is associated with severe environmental problems, such as noise, traffic, and social pressure [12], which promote people to seek solace in green space and other natural environments. At the same time, the positive and attractive aspects of the UGS (e.g., pleasant experience in nature, spacious sports fields, meeting places) are also one of the reasons attracting visitors. Furthermore, other values of UGSs including educational value and ecological protection value also have an impact on the choice of visitors. Therefore, the evaluation of UGSs should be carried out from multiple aspects. Among published literary works that focused on the health benefits and equity of parks, researchers have adopted the Community Park Audit Tool (CPAT), Environmental Assessment of Public Recreation Spaces (EAPRSs), and other methods to evaluate the quality of urban green space [13,14]. Evaluation indexes of UGS are widely acknowledged in previous studies, such as aesthetics value, ecological value, public service quality, tourist experience quality, and other factors [15–18], which are mostly related to internal park details and comprehensive indexes with emphasis on the management and construction of UGSs, however. In a recent study, Markevych et al. [19] proposed and emphasized the necessity of research on UGSs and health, considering the accessibility, quality, scale, and pattern use of UGSs comprehensively, in order to maximize the health benefits of building environment interventions. However, to date, few UGS evaluation systems have worked on the health of residents around green spaces based on research on PA. In this study, we analyze factors, including aesthetic and attractions, natural world experience, nature conservation, encouraging physical activity, cultural value, and social value, of urban green space based on the residents' daily activities in UGSs and correspondingly establish a residents' physical activity-oriented UGS evaluation system.

Despite the scale, type, and surrounding environment of green space, the potential effects of a UGS on residents' health may also be different based on its internal landscape structure [20,21]. It has been proved that the size of green space brings different perceptions to visitors. Visitors prefer to head to larger urban green spaces, as small-scale green spaces are more likely to be perceived as private properties [22]. Of the various types of green space cover that have been studied (e.g., forests, wetlands, farmlands, rangelands), forested areas provided visual stimuli and significant stress reduction, which have the most significant impact on mental health [5]; however, distinct studies may yield dissimilar outcomes. Though the criteria of landscape structure evaluation are different, landscape diversity and the percentage of each component are the important aspects. The increased complexity and variability resulting from landscape diversity contribute to a stronger visual preference effect and foster an emotional and spiritual connection between visitors and the environment [23].

The social value of UGSs can be reflected in the initiative and frequency of people visiting green space [24], which could contribute to residents' health positively [25]. From this aspect, the accessibility of a UGS may greatly affect the willingness of residents to visit the green space [26–28], which means it is necessary to be able to approach or enter it more conveniently in order to make effective use of the public UGS system. For example, the WHO proposed a method for measuring the health benefits of public UGS systems based on data from the residential population area within a radius of 300 m (or a 5 min walk) around green space in 2016 [29], which indicates that residents living at a certain distance

to the green space can easily enter into it. It is reported that residents who live near green spaces engage in a variety of activities such as daily sports and dog walking, while people tend to stay longer and are more likely to engage in active recreational or social activities when visiting distant parks, especially larger city parks [30]. In other words, the frequency of residents visiting green areas for activities and the type of sports they play are related to the distance from the UGS.

Quantitatively investigating the quality of UGSs is facilitated through the utilization of some computer technologies such as big data analysis, image processing, and machine learning [31,32]. Image-based semantic segmentation technology can be used to distinguish different landscape features and provide effective guidance on future urban planning and design combined with public perception, which is a new development trend that is more applied to natural landscapes at present. For example, Chen et al. created a dataset of community-scale UGSs based on the semantic segmentation method to facilitate green space design in future community planning [33]. Wang et al. collected street view images and evaluated the quality of green space using machine learning algorithms to analyze the relationship between street view greening and the social economic conditions of communities [34]. The application of machine learning technology provides effective technical support for the realization of high-precision resolution for natural elements. Based on the selection of models and datasets adapted to describe various landscape elements in UGSs, the application of semantic segmentation in different application scenarios can be widely expanded, where a large experimental space for exploration is promising.

It is necessary to determine the corresponding weights of indexes when constructing an evaluation model for UGSs. Former evaluation models have relied on subjective approaches such as satisfaction surveys, questionnaire surveys, and field investigations, which lack accuracy and objectivity in index weights calculation. In this study, the Uncertainty Analytic Hierarchy Process (UAHP) and Entropy Weight Method (EWM) are used to determine the subjective and objective weights of evaluation indexes to balance the subjectivity and objectivity of the results. The UAHP method is a multi-criteria decision-making method that can comprehensively consider the uncertainty and fuzziness of index factors [35]. Its interval judgment matrix can reduce aleatory uncertainties in the index weight determination compared to the more commonly used Analytic Hierarchy Process (AHP) method [36]. However, the UAHP method can only calculate interval weights, which need to be turned into crisp values for subsequent evaluation. To address this issue, we incorporated the concept of deviation degree into the UAHP to construct an optimization model for resolving the subjective weights. Subsequently, we employed the Genetic Algorithm (GA), which can solve the optimization model accurately and quickly, to determine the optimal subjective weight. The Genetic Algorithm (GA) is an efficient and parallel heuristic global optimization algorithm, which can control the search process adaptively in the solution space to approach the optimal solution successively and finally obtain the approximate optimal solution [37]. On the other hand, the Entropy Weight Method (EWM) is an objective weighting method, which mainly measures the disorder level of the index system through the information entropy and evaluates the distribution of each evaluation index from an objective perspective [38]. Game theory is a branch of modern mathematics capable of considering the predicted and actual behavior of individuals under study while searching the optimization strategies [39]. Herein, a combinatorial weighting method, named the Improved Combined Weighting Method of Game Theory (ICWGT), is employed to combine the index weights obtained by the subjective and objective weighting method, thus aiming to achieve the most reasonable index weights in the end.

Overall, this study aims to establish a UGS evaluation model oriented by residents' physical activity, and the steps and contents of each chapter are distributed as follows: Section 2 of this paper mainly describes the selection of target green spaces, as well as the process and method of obtaining data. Section 3 describes the construction process of the entire evaluation model: Section 3.1 mainly focuses on the selection of evaluation indexes of UGSs; Section 3.2 describes the determination process of evaluation index weight and

the construction of the model. Section 4 describes the analysis of the results, including the comparative analysis of the weights of the solved indexes. Section 5 includes the conclusions and future prospects.

## 2. Research Area and Data Acquisition

### *2.1. Site Selection*

This study was carried out to establish a framework for assessing UGSs by focusing on the residents' physical activity levels in the Changsha City of China. As shown in Figure 1, Changsha City is the capital of Hunan Province, located in the central part of China. The city is renowned for its plentiful water resources and favorable geographical setting, earning it the moniker "City of Mountains and Water". It is noteworthy to highlight that the urbanization rate of Changsha has achieved 77.59%, indicating the rapid progression of its urbanization process [25]. Additionally, Changsha City boasts a forest coverage rate of 55%, positioning it within the top three provincial capitals nationally according to pertinent statistics. The health literacy rate is a comprehensive indicator that reflects economic and social development and the health level of the residents of China. In 2022, the residents' health literacy rate of Changsha attained a level of 31.24%, indicating that 31 out of every 100 residents aged 15-69 possess fundamental health literacy here. Moreover, more than 40 percent of residents participate in physical activities, achieving the target level outlined in the Healthy China 2030 Plan ahead of schedule.

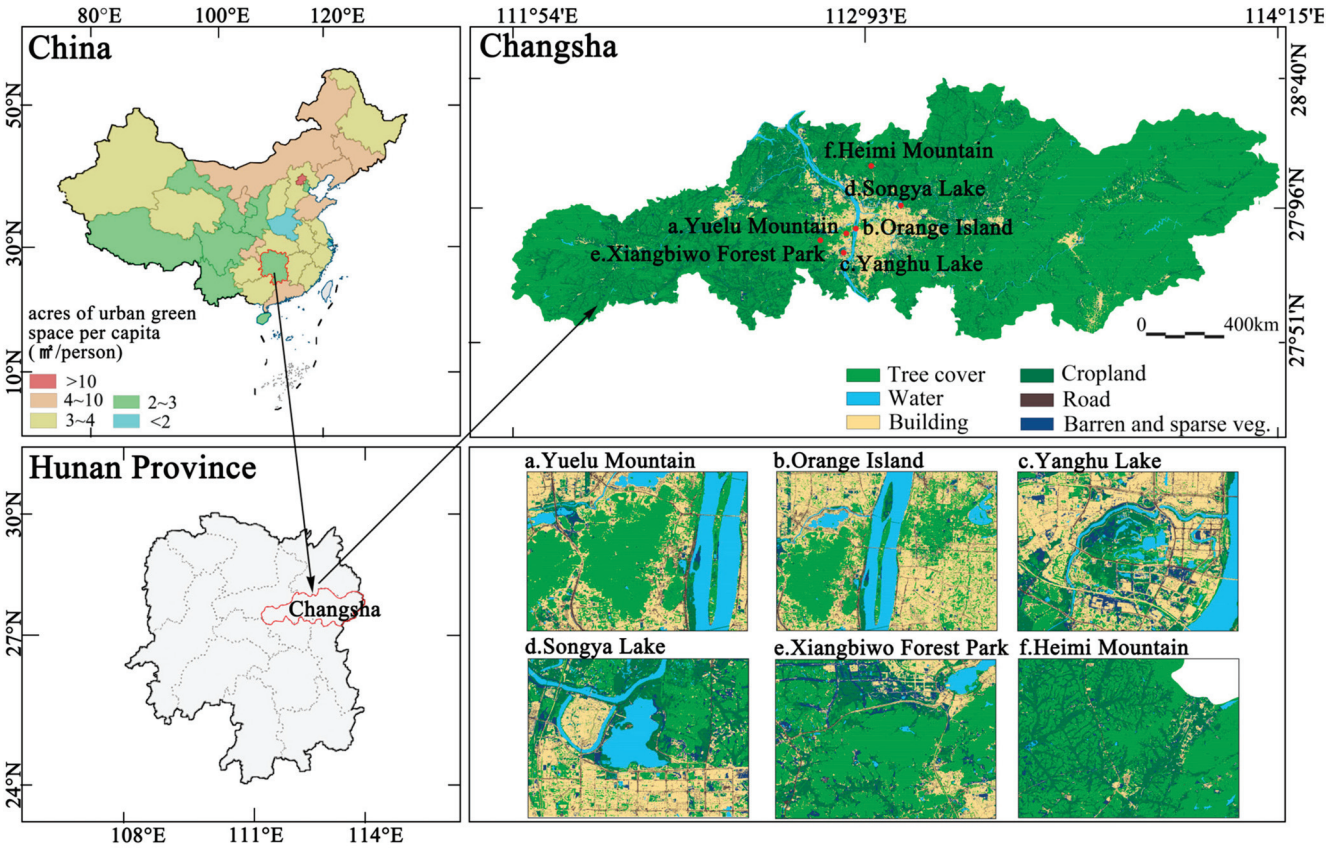



**Figure 1.** Location of the research object.

Across the city, we selected six UGSs with different proportions of landscape structures for subsequent investigation. Among them, Yuelu Mountain and Orange Island are both characterized by a comprehensive landscape structure and attract a large number of tourists as national scenic spots. Yanghu Lake and Songya Lake are surrounded by residential areas with more convenient transportation accesses, primarily featuring blue space (water body). Xiangbiwo Forest Park and Heimi Mountain are expansive forest parks in Changsha city,

boasting abundant vegetation coverage and significant green space (Figure 1). The above target UGSs exhibit a diverse landscape structure that may elicit varying levels of visiting interest/attraction in the surrounding residents. Consequently, these six green spaces were chosen as the subjects of investigation in this paper.

### *2.2. Image Acquisition*

Initially, the target data intended for analysis were acquired from images of the six UGSs through data mining technologies [40]. Previous studies had attempted to obtain and analyze specific data through social platforms such as Twitter and Instagram using data mining technologies [41,42]. The names of the six UGSs were employed as keywords to retrieve publicly available picture data from Weibo ® v13.3, Red® v7.81 (named LittleRedBook in China), and other prominent social media platforms in China. Weibo® v13.3 is the largest social media platform in China, and Red® is loved by younger users, with higher user growth and activity. The data collected cover the period from April 2021 to April 2023, utilizing the Baidu® v13.6 search engine at http://www.baidu.com, accessed on 4 May 2023, and were manually screened, with irrelevant picture data deleted. After the screening process, a total of 2413 images related to the target city green spaces were obtained and further processed.

### *2.3. Semantic Segmentation*

In recent years, deep learning has been widely used in the field of semantic segmentation as a common artificial intelligence technology, which has attracted the attention of researchers. The core technology of this field is the automatic analysis and feature learning based on a large amount of data, which can effectively extract the low-, middle-, and high-level information in the image and realize the prediction classification at the pixel level under the condition of semantic expression [43]. Due to its powerful image processing capabilities, deep learning technology was used to automate the processing of the 2413 images that were collected.

In order to extract urban green landscape features, a Full Convolutional Neural Network (FCN) based on the ADE-20KFootnote1 dataset training model was used to segment the features in each photo semantically and obtain the area ratio of each semantic target. The FCN can predict the semantic properties of each pixel in an image, which can produce the segmentation of natural objects. By segmenting street view images into various detailed sub-scenes using the FCN, including bodies of water, roads, trees, or other natural objects, it is possible to encompass up to 151 categories of green landscape structures (including the "unknown" category). Herein, the ADE-20K dataset published by MIT [44] was used to train the FCN. Then, the well-trained FCN was integrated into a proposed human–machine adversarial scoring framework, which provided 151-dimensional feature vectors for the random forest to fit the scoring preferences of human annotators and gave corresponding recommended scores.

As in the semantic segmentation process shown in Figure 2, the 2413 images covering the 6 UGS areas were segmented and visualized in this study. After classifying the identified information, we distinctly counted the quantity of pixels within each category represented by a unique color. The visual proportion of each landscape feature was precisely determined according to the quantitation results. There were 12 related landscape features finally selected from 151 categories of green landscape structures, which included tree, grass, mountain, plant/plant life, water, rock, river, flower, hill, dirt track, land/ground, and lake. The initial proportions of the corresponding features in the six UGSs after semantic segmentation are shown in Table 1.

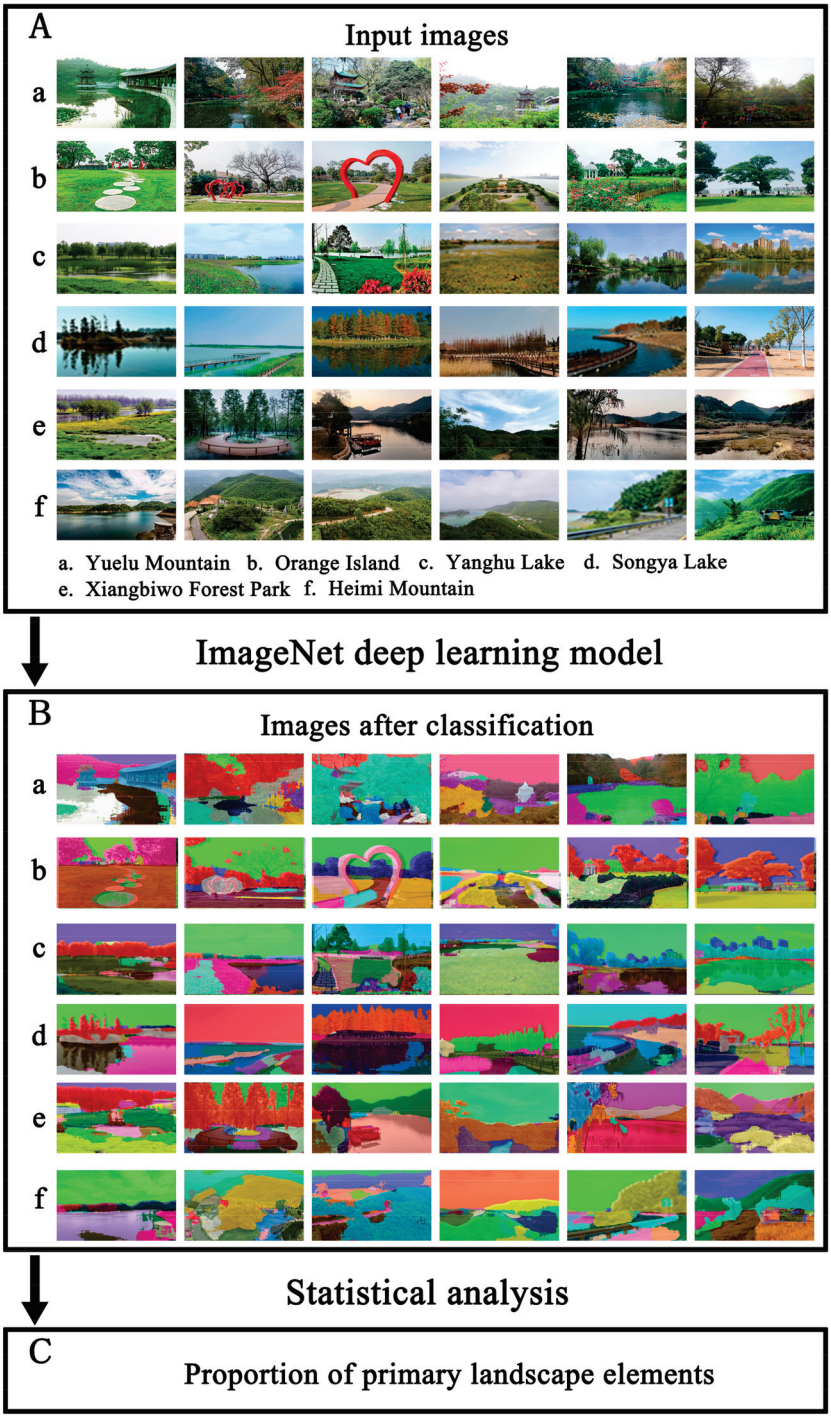



**Figure 2.** Semantic segmentation process. (**A**) Input images; (**B**) Images after classification; (**C**) Proportion of primary landscape elements.

The data presented in the table represent the initial results obtained after semantic segmentation; with only 12 out of 151 landscape structure categories being considered, the figures may be understated. Within the selected 12 landscape structure categories, there may be significant discrepancies between the data due to individuals' preferences when taking photographs. As a result, a stratified counting approach was employed to reduce errors. The proportion distributions of individual features among the total 12 features are illustrated in Figure 3.

**Table 1.** The proportion of landscape structure features in the six UGSs.

| Landscape Structure Features | Yuelu Mountain | Orange Island | Yanghu Lake | Songya Lake | Xiangbiwo Park | Heimi Mountain |
|---|---|---|---|---|---|---|
| Tree | 0.4418 | 0.1370 | 0.1429 | 0.1022 | 0.2646 | 0.1948 |
| Grass | 0.0116 | 0.0596 | 0.0503 | 0.0573 | 0.0214 | 0.0156 |
| Dirt Track | 0.0006 | <0.0001 | <0.0001 | 0.0001 | 0.0006 | 0.0004 |
| Land | 0.0010 | 0.0038 | 0.0013 | 0.0004 | 0.0034 | 0.0120 |
| Stone | 0.0074 | 0.0052 | 0.0036 | 0.0045 | 0.0065 | 0.0062 |
| Plant | 0.0466 | 0.0265 | 0.0507 | 0.0190 | 0.0252 | 0.0257 |
| Flower | 0.0044 | 0.0018 | 0.0023 | 0.0028 | 0.0009 | 0.0006 |
| Mountain | 0.0208 | 0.0306 | 0.0038 | 0.0126 | 0.0680 | 0.1015 |
| Hill | 0.0036 | 0.0031 | 0.0001 | 0.0011 | 0.0089 | 0.0148 |
| River | 0.0220 | 0.0128 | 0.0360 | 0.0169 | 0.0324 | 0.0085 |
| Water | 0.0397 | 0.0594 | 0.1245 | 0.0632 | 0.1018 | 0.0326 |
| Lake | 0.0030 | 0.0020 | 0.0105 | 0.0048 | 0.0099 | 0.0023 |

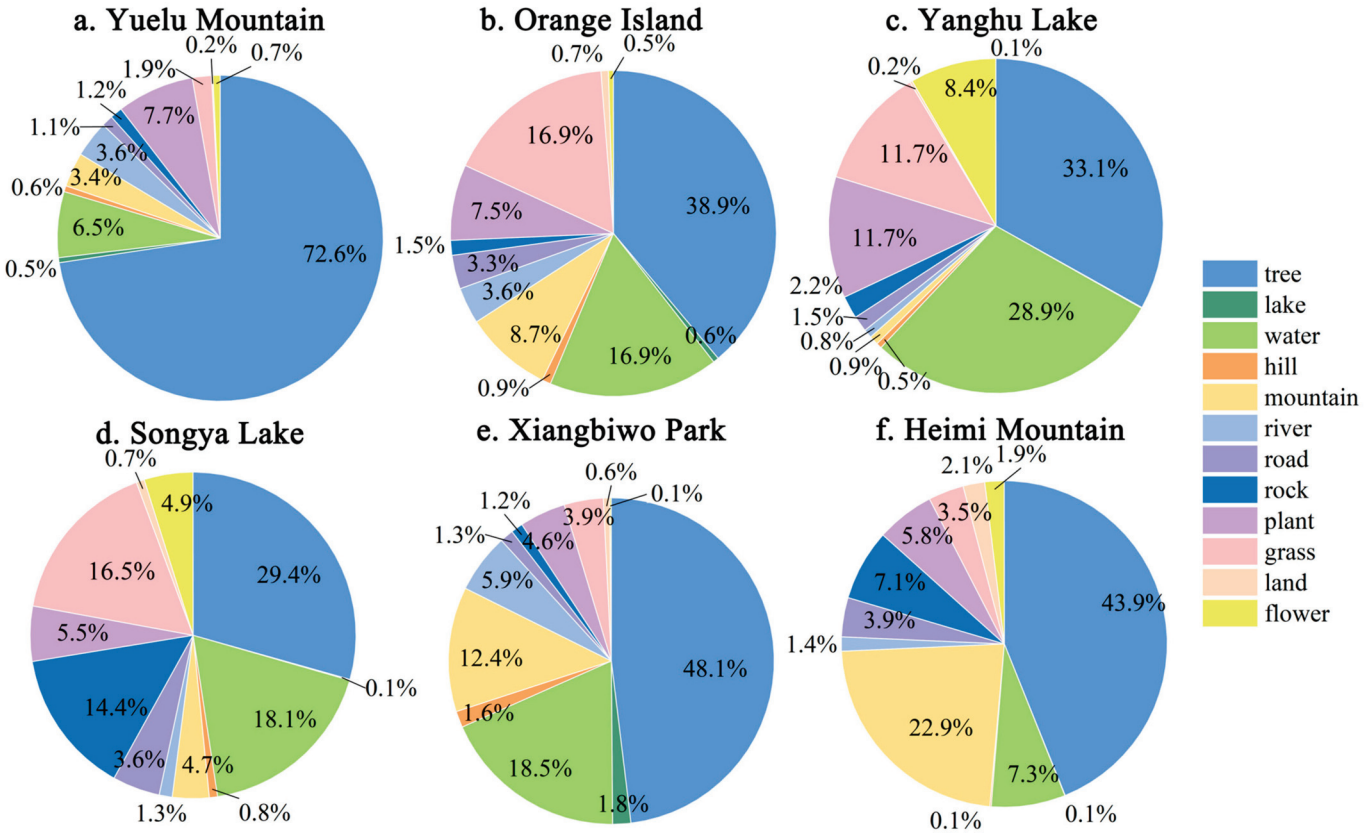



**Figure 3.** The proportion distribution of individual features in the six UGSs.

### *2.4. Data on Residents' Physical Activity*

The community life circle generally refers to the spatial range composed of activities that occur to maintain the daily life of residents. As an important space carrier to meet the needs of residents' daily public services and diversified activities, the planning practice of the living circle has become increasingly extensive around the world in recent years. At the same time, the planning concept and corresponding practice of "15 min city" and "15 min community life circle" were produced [45]. As China's urban development strategy turns to "people-foremost", there has been an increased focus on investigating and discussing urban community life circle planning.

Keep® v7.47is a widely used and versatile App mainly used for fitness and dating in China with more than 200 million registered users. This study quantitatively assessed the distribution characteristics of urban physical activity by using public records of track information and exercise frequency in the software. The software offers a feature for creating routes, allowing users to generate a new movement route mode while enabling other users to synchronize their movement data upon finishing the same route type. So, it is feasible to make statistics of various movements of surrounding residents based on the documented routes within the software. According to the route data collected, running, walking, and bike-riding are the most frequently recorded route types within the data in the Changsha urban area (in the six UGSs of Changsha). This study only collected the number of completions and respective proportion of the routes that were publicly disclosed within the software and used ArcGIS10.2® to picture the route trajectories for subsequent studies, without any potential invasion or conflicts of personal privacy of the users. In accordance with the principles of the "15 min community life circle", this study focused on the route data within a 1.5 km radius surrounding the six UGSs mentioned above. The research data were collected in October 2023, and by the end of the data collection, a total of 99 routes and 1,697,043 exercise records were obtained, including 1,437,988 running, 166,683 walking, and 73,753 bike-riding records. The relevant data are reflected in Table 2.

**Table 2.** Statistics of recorded physical activity data.

| | Yuelu Mountain | Orange Island | Yanghu Lake | Songya Lake | Xiangbiwo Park | Heimi Mountain | Total |
|---|---|---|---|---|---|---|---|
| Total sports attendance [person-time] | 888,012 | 311,080 | 230,176 | 256,058 | 11,607 | 110 | 1,697,043 |
| Number of trajectories | 33 | 20 | 23 | 14 | 8 | 1 | 99 |
| Frequency of running [person-time] | 781,929 | 261,581 | 205,913 | 178,976 | 9576 | 13 | 1,437,988 |
| Frequency of walking [person-time] | 102,769 | 36,042 | 20,689 | 23,773 | 2018 | 12 | 166,683 |
| Frequency of bike-riding [person-time] | 3315 | 13,457 | 3574 | 53,309 | 13 | 85 | 73,753 |

Figure 4 depicts a trajectory route map obtained by picturing the movement trajectories within a 1.5 km radius around the target green space in ArcGIS. The more the line's color approaches red, the higher the number of individuals observed exercising along this trajectory.

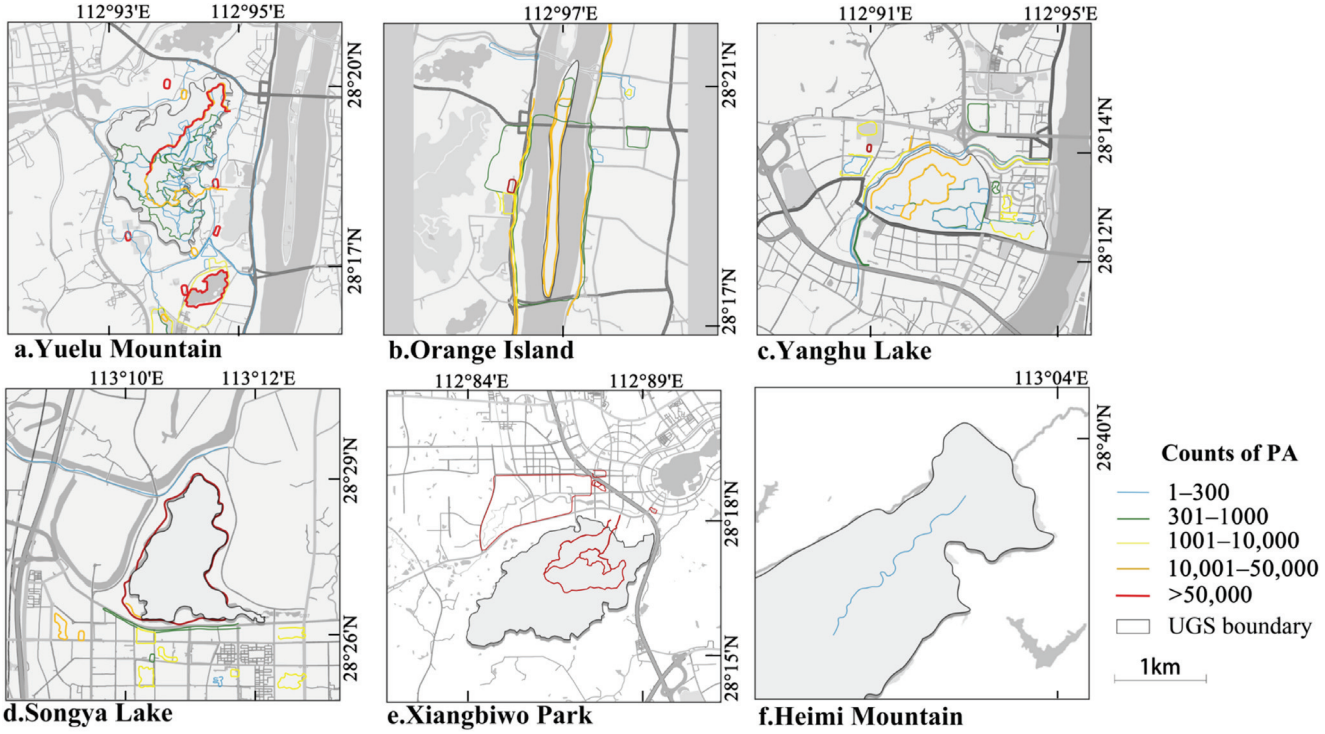



**Figure 4.** Route records and their frequency in the six UGSs.

## 3. The PA-Oriented UGS Evaluation Model

The construction of the UGS evaluation model was conducted in two parts, as follows:

1. For the selection of UGS evaluation indexes, the scale of the green space itself and the impact of different types of landscape structures on residents' movement were considered firstly. The statistical analysis of the landscape structure of the target green space was conducted by Python® 3.1.15 and semantic segmentation technology. Secondly, the accessibility of roads within 1.5km around the green space was taken into consideration, which can represent the spontaneity level of residents voluntarily visiting the green space. The PAs of surrounding residents were measured using the Keep App to analyze the positive impact of UGS. Finally, we focused on how the cultural value or natural conservation value of the green space itself influenced the PA motivation of residents.
2. In terms of the establishment of the evaluation model, a GA-optimized Uncertainty Analytic Hierarchy Process (UAHP) method and Entropy Weight Method (EWM) were used to determine the subjective and objective weights of the evaluation indexes, respectively. The Improved Combined Weighting Method of Game Theory (ICWGT) realizes the optimal combination of the subjective and objective weights, which can minimize their deviations and ultimately receive the optimal combined weights. In this way, an index-weight-based, subjective, objective-cognition-considered, and residential PA-related evaluation model for UGS was established herein.

The research method and process are shown in Figure 5:

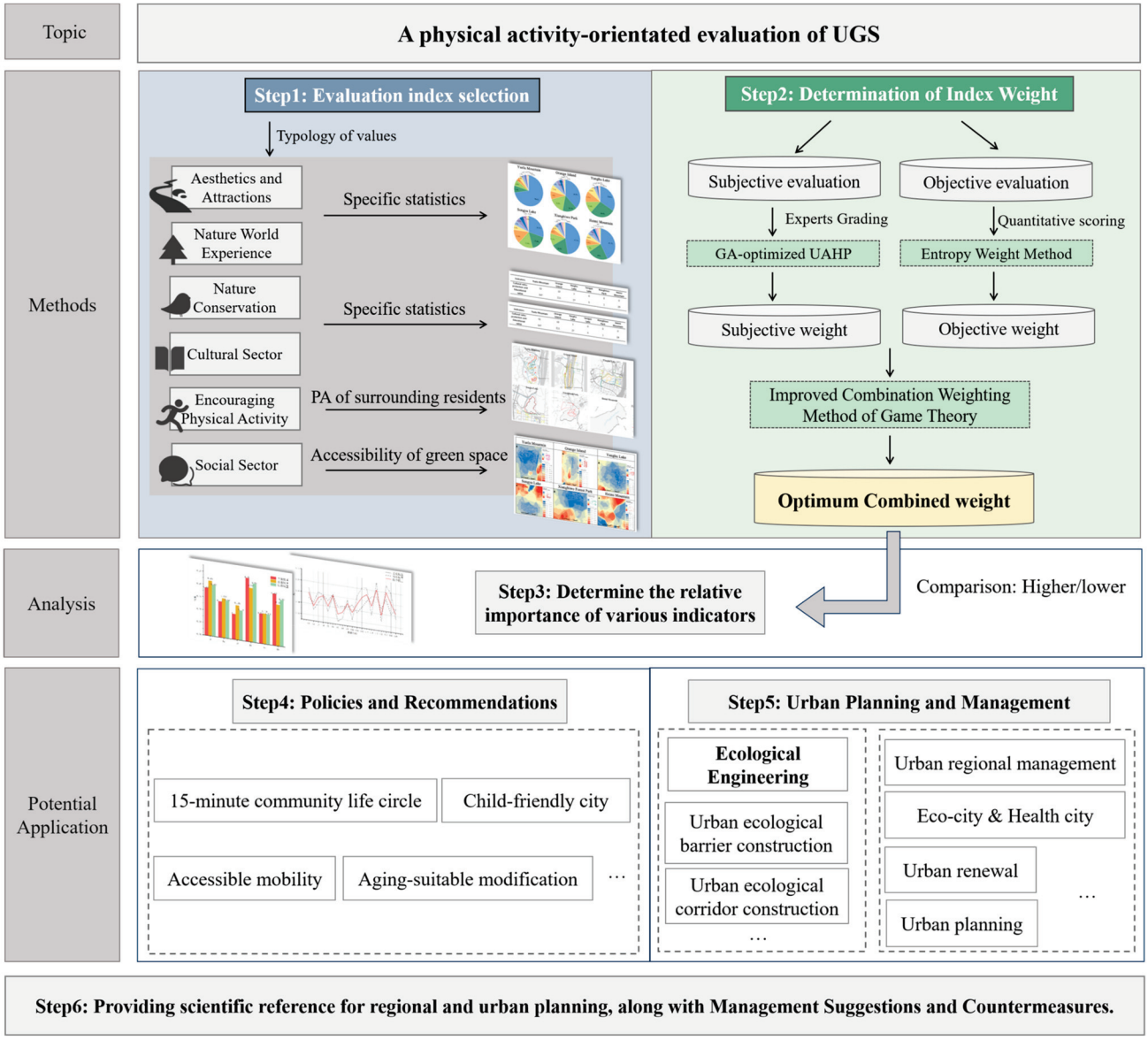



**Figure 5.** The flowchart of proposed evaluation model.

### *3.1. Determination and Quantitation Methods of Evaluation Indexes*

UGS is considered a crucial component in China's ecological civilization construction; an increasing number of studies have already begun to pay attention to the social value realization and evaluation of UGS, where the relationship between ecosystem social value and environmental landscape features is the current trend in studies on ecosystem cultural services [46]. After discussion and confirmation with experts majored in ecosystem cultural services, we classified the UGS evaluation system from the perspective of ecosystem cultural services as follows:

- Aesthetic and attractions (e.g., places that are visually attractive);
- Encouraging physical activity (e.g., places provide opportunities for physical activity);
- Native conservation (e.g., places' value for the protection of native plants and animals);
- Nature world experience (e.g., places to experience the natural world);
- Cultural value (e.g., opportunities to express and appreciate culture or cultural practices);
- Social value (e.g., opportunities to interact with other people).

Compared with the widely used subjective questionnaire method in previous studies, several quantitative and objective landscape evaluation methods are integrated and em-

ployed in the following investigation to reflect the ecosystem cultural service level of UGS. The related public images were gathered by means of image data mining and semantic segmentation technology; then, the visual proportion of different landscape elements was statistically measured by counting pixels, so as to represent the aesthetic value and nature world experience value of UGS. The following are some key indexes which quantify each evaluation dimension: (1) greenery ratio (GR) and green space visual exposure index (GVI) represent the area of natural environment and biological habitat area to a certain extent, which imply positive significance in nature protection; (2) the statistical data of movement routes of surrounding residents can indirectly reflect the value of this green space in PA; (3) the surrounding green space with high walking accessibility can be regarded as capable of providing better neighborhood social services; and (4) the cultural value of UGS can be evaluated by the number of cultural relic protection units and the number of published papers with the target UGS as the key words. The data obtained from all the above methods and their processes are described below.

#### 3.1.1. Aesthetics and Attractions and Nature World Experience Value of UGS

After using the semantic segmentation technology on the acquired images with the method described in Section 2.3, we can calculate the area of different landscape structures in each picture of the target green spaces. According to the UGS landscape classification method proposed by Pablo Knobel et al. in 2021 [47], the 12 landscape elements above are divided into two dimensions: aesthetics and attractions and nature world experience. The former one represents the evaluation of the beauty and attractiveness of the UGS, while the other is used to evaluate the natural attributes of the green space, such as the coverage degree of trees and grassland.

To reduce the influence induced by the uncertainties and potential errors that occurs during program identification, it is stipulated that only non-vegetation landscape elements (mountain, river, etc.) that account for more than 10% of the image area and vegetation landscape features (tree, grass, flower, etc.) that account for more than 20% of the image area will be considered as valid and counted in the total; otherwise, they will not be counted. The statistical results are presented in Table 3:

**Table 3.** Landscape feature statistics of the six UGSs.

| **Indexes** | | **YM** | | **OI** | | **YL** | | **SL** | | **XP** | | **HM** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **P** | **C** | **P** | **C** | **P** | **C** | **P** | **C** | **P** | **C** | **P** | **C** |
| Aesthetics and attractions | Plant | 0.0466 | 24 | 0.0265 | 9 | 0.0507 | 26 | 0.0190 | 10 | 0.0252 | 13 | 0.0257 | 13 |
| | Flower | 0.0044 | 4 | 0.0018 | 0 | 0.0023 | 0 | 0.0028 | 3 | 0.0009 | 0 | 0.0006 | 0 |
| | Mountain | 0.0208 | 30 | 0.0306 | 43 | 0.0038 | 2 | 0.0126 | 15 | 0.0680 | 142 | 0.1015 | 73 |
| | Hill | 0.0036 | 3 | 0.0031 | 0 | 0.0001 | 0 | 0.0011 | 0 | 0.0089 | 13 | 0.0148 | 6 |
| | River | 0.0220 | 35 | 0.0128 | 18 | 0.0360 | 49 | 0.0169 | 24 | 0.0324 | 6 | 0.0085 | 38 |
| | Water | 0.0397 | 56 | 0.0594 | 99 | 0.1245 | 163 | 0.0632 | 117 | 0.1018 | 43 | 0.0326 | 111 |
| | Lake | 0.0030 | 2 | 0.0020 | 4 | 0.0105 | 1 | 0.0048 | 1 | 0.0099 | 1 | 0.0023 | 11 |
| Nature world experience | Tree | 0.4418 | 375 | 0.1370 | 115 | 0.1429 | 76 | 0.1022 | 77 | 0.2646 | 151 | 0.1948 | 158 |
| | Grass | 0.0116 | 3 | 0.0596 | 51 | 0.0503 | 21 | 0.0573 | 43 | 0.0214 | 4 | 0.0156 | 7 |
| | Dirt Track | 0.0006 | 1 | <0.0001 | 0 | <0.0001 | 0 | 0.0001 | 0 | 0.0006 | 0 | 0.0004 | 0 |
| | Land | 0.0010 | 1 | 0.0038 | 1 | 0.0013 | 1 | 0.0004 | 1 | 0.0034 | 1 | 0.0120 | 3 |
| | Stone | 0.0074 | 8 | 0.0052 | 4 | 0.0036 | 2 | 0.0045 | 5 | 0.0065 | 7 | 0.0062 | 6 |

Note: YM refers to Yuelu Mountain; OI refers to Orange Island; YL refers to Yanghu Lake; SL refers to Songya Lake; XP refers to Xiangbiwo Park; HM refers to Heimi Mountain. P = each landscape feature's pixels/total pixels of all of pictures; C is the picture counts of each landscape feature.

3.1.2. Nature Conservation Value

Within the urban landscape, destinations such as Yuelu Mountain, Orange Island, Yanghu Lake, Songya Lake, Heimi Forest Park, and Xiangbiwo Forest Park draw considerable foot traffic from locals and tourists alike. To gauge the scale of the natural environment and the richness of biological habitats, metrics like the green space coverage ratio (GR) and the green space visual exposure index (GVI) serve as reliable indexes. Likewise, the diversity of plant species within these green areas underscores their significance in terms of nature conservation. In light of this, the evaluation of green spaces' conservation value revolves around three key indexes: GR, GVI, and the diversity of plant species, each offering valuable insights into the ecological significance of the UGS.

The index for green space coverage rate has the capability to indicate the proportionate expanse of greenery. To obtain relevant data regarding the GR, the ArcGIS 10.2® model was utilized, and the Baidu map was analyzed following geometric coordinate correction and projection conversion. All urban green spaces, agricultural green spaces, forests, and nature reserves are considered green spaces. The index for green space coverage rate had the capability to indicate the proportionate expanse of greenery. Residences and their immediate surroundings within a 10 m radius fall under the urban infrastructure designation; consequently, the foliage adjacent to dwellings did not contribute to the calculation of green space coverage rate.

There are various methods that can be employed to assess the extent of ecological exposure; this study utilizes the GVI assessment tool to quantify the visible greenery from diverse vantage points at ground level. As the snapshots sourced from social media were typically captured through a human lens, the quantification of greenery within a particular location is indicative of its GVI. The number of plant species in the green space was acquired through the Google Scholar data retrieval tool. The statistics are shown in the following Table 4:

**Table 4.** The nature conservation indexes and corresponding values of each UGS.

| Indexes of Nature Conservation | Yuelu Mountain | Orange Island | Yanghu Lake | Songya Lake | Xiangbiwo Park | Heimi Mountain |
|---|---|---|---|---|---|---|
| GR | 92% | 86% | 90% | 91.80% | 85.40% | 73.90% |
| GVI | 50.45% | 22.49% | 24.62% | 18.13% | 31.21% | 23.67% |
| Number of plant species | 977 | >1000 | 639 | 489 | 430 | 673 |

Notes: GR is the vertical projection area of all vegetation excluding superimposed situations to the total area in a certain range; GVI is the vegetation area in the human view to the total human view area.

3.1.3. Value of Encouraging Physical Activity

Based on the exercise-related route data obtained with Keep® (during the period from April to October 2023), the present physical activity value and potential movement possibilities of UGSs were systematically analyzed. The person-time of individuals utilizing the movement routes, together with the quantity of the routes, was used to convey the movement patterns of the nearby inhabitants. The overall movement in the area can be reflected by adding up the mileage of all users; the greater the total mileage, the better the PA is considered in general. Simpson's diversity index is a reliable metric for determining the variation in physical activities such as running, walking, and bike-riding in the given region. The index is an accurate reflection of the level of diversity present therein; specifically, the closer the index is to 1, the lower the rate of diversity in sports present in that area. The degree of difficulty in traversing is indicated by computing the proportion of the cumulative altitude gain to the overall distance. Essentially, the more challenging the task, the more rigorous the expectations are for the fitness of the individual engaging in it.

Simpson's diversity index was initially implemented to evaluate the variety of species within an ecosystem. Its fundamental concept is to determine an index that characterizes the diversity level of a given sample, taking into account the proportional degree of

contribution that each species in the sample holds and assigning a quantifiable measure of the likelihood of randomly extracting two individuals from this sample that will belong to the same specific species. The formula is as follows:

$$\text{Div} = \sum_{i=1}^{S} \left( \frac{n_i(n_i - 1)}{N(N-1)} \right) \quad (1)$$

where $S$ is the total number of species; $N$ signifies the total number of individuals across all the species found, while $n_i$ denotes the count of individuals for the $i$-th species within the population. The index is evaluated on a scale of 0 to 1, whereby 0 indicates an infinite range of diversity, and 1 indicates no diversity. A higher index value is indicative of lower diversity within the ecosystem. Table 5 presents the data concerning the promotion of the physical activities of neighboring inhabitants, after data preprocessing.

**Table 5.** Indexes of residents' physical activity.

| Indexes of Residents' PA | Yuelu Mountain | Orange Island | Yanghu Lake | Songya Lake | Xiangbiwo Park | Heimi Mountain |
|---|---|---|---|---|---|---|
| Residents' participation in PA [person-time] | 888,012 | 311,080 | 230,176 | 256,058 | 11,607 | 110 |
| Outdoor activities [km] | 769,853.12 | 686,567.55 | 283,398.00 | 1,636,319.28 | 13,008.35 | 293.70 |
| Sports diversity (Div) | 0.785 | 0.722 | 0.809 | 0.541 | 0.711 | 0.616 |
| Difficulty of PA | 0.061 | 0.020 | 0.014 | 0.018 | 0.072 | 0.041 |

Note: difficulty of PA = cumulative altitude gain/the overall distance.

#### 3.1.4. Accessibility of UGS

The accessibility of green space is an important component in evaluating the quality of UGS. The accessibility of green spaces is the key standard indicating the disparity of surrounding environmental construction quality and directly impacts on the inclination of residents towards such areas for exercise and social requirements [48,49]. Generally, the ones which are not easily accessible are scarcely frequented and satisfy fewer social needs.

This study employs Origin–Destination cost matrix solver within the GIS framework to calculate and analyze the accessibility of residents commuting on foot to green space, which can identify and measure the shortest path from multiple initial and final access points along a network. After the urban road network was imported, the main roads, secondary roads, and branch roads were selected as the viable computation paths, and all the intersection junctures were set as both the starting and the destination point. The normal walking pace of 6 km/h was set as the computation standard of velocity, whilst the target area was confined within a radial distance of 1.5 km to the target UGS. As a result, the average time from each intersection to other destinations is the criterion for evaluating the accessibility of the particular point. The analysis results of the six target UGSs' accessibility are shown in Figure 6. The statistical chart depicts the varying levels of accessibility across different locations, ranging from maximum to minimum values, along with the average accessibility within the specified range. These data are further detailed in the accompanying Table 6.

**Table 6.** Accessibility of six UGSs.

| Indexes of Accessibility | Yuelu Mountain | Orange Island | Yanghu Lake | Songya Lake | Xiangbiwo Park | Heimi Mountain |
|---|---|---|---|---|---|---|
| Accessibility Mean [min] | 47.83 | 39.04 | 32.63 | 41.47 | 45.80 | 51.69 |
| Accessibility MIN [min] | 38.64 | 20.09 | 23.67 | 15.12 | 29.74 | 1.09 |
| Accessibility MAX [min] | 77.02 | 70.2 | 63.76 | 77.55 | 118.8 | 71.3 |

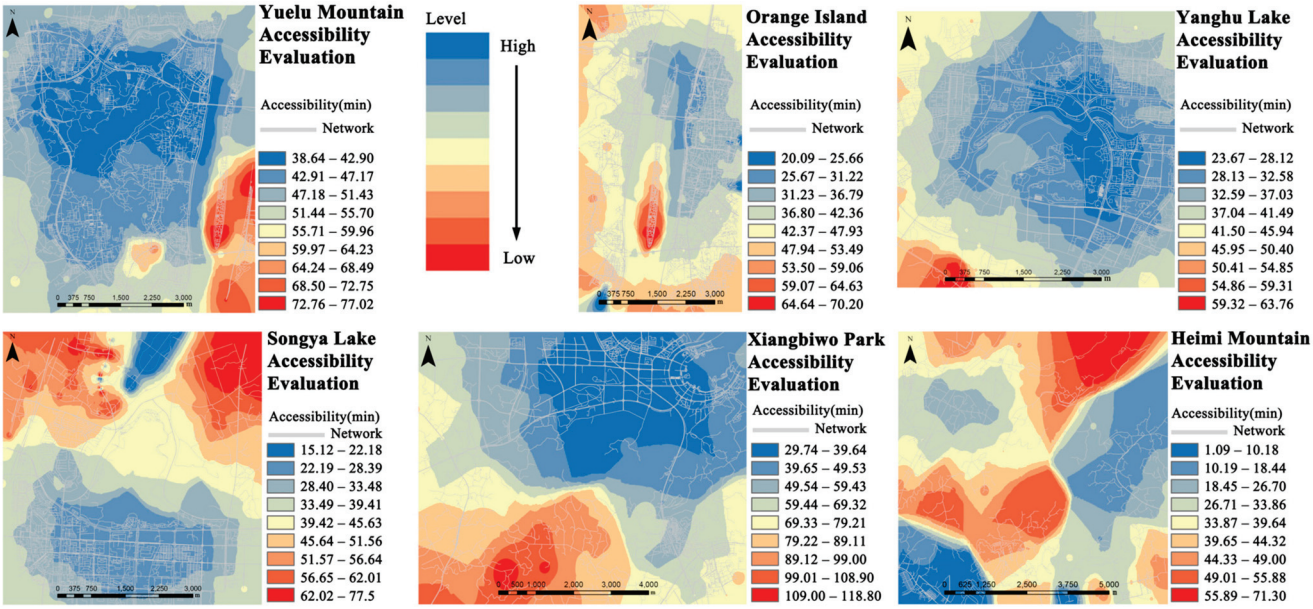



**Figure 6.** Accessibility map of six UGSs.

#### 3.1.5. Culture Value of UGS

When assessing the humanistic worth of a green space, the quantity of cultural relics that are preserved, the prevalence of cultural allusions pertaining to the area, and the level of cultural and educational importance of the place are typically taken into account. Among these factors, the number of cultural relics safeguarded and the cultural and educational significance bear considerable weight as major draws for individuals who patronize the location. Therefore, this study represents the cultural value of the UGSs by counting the number of cultural relic protection units and the number of publications (both in Chinese and English) with the keywords of the urban green space. The statistical results are presented in Table 7:

**Table 7.** Indexes of cultural value.

| Indexes of Culture Value | Yuelu Mountain | Orange Island | Yanghu Lake | Songya Lake | Xiangbiwo Park | Heimi Mountain |
|---|---|---|---|---|---|---|
| Cultural relics protection units [num] | 52 | 10 | 1 | 0 | 0 | 0 |
| Educational value [num] | 347 | 211 | 27 | 5 | 1 | 29 |

### *3.2. Construction of Evaluation Index System and Corresponding Weights Calculation*

To guarantee the scientific precision and reliability of evaluating the value of UGSs, the approach utilized in this study involved conducting both subjective and objective evaluations on six target green spaces through the UAHP and EWM. This enabled the acquisition of corresponding subjective and objective weights, reducing the margin of error caused by subjective evaluations. The weight of the UAHP technique was evaluated by experts and optimized through GA. The primary purpose of the EWM is to derive an objective targeted value via an assortment of appraisal techniques for green space; some of these methods include green space accessibility, greenery ratio, the extent of residents' involvement in green space recreational activities, etc. After a thorough analysis and evaluation of the value of green space in physical activities, the ideal weight for a combination of subjective and objective factors was derived using the Improved Combination Weighting Method of Game Theory (ICWGT). This achieves the goal of a comprehensive and holistic approach to the assessment of green spaces in PA, providing an all-encompassing perspective.

3.2.1. Uncertainty Analytic Hierarchy Process

The Uncertainty Analytic Hierarchy Process (UAHP) can resolve uncertainties such as randomness, ambiguity, and incomplete information in decision making [50]. In this paper, the UAHP method is used to calculate the subjective weight of each index. Contrary to the conventional AHP approach, the UAHP method employs interval numbers for the resolution of the weight vector instead of specific values. The UAHP technique is more precise and impartial in comparison to the AHP approach, as it can effectively reduce the errors and bias arising from the single subjective evaluation value. For example, J. Awad and C. Jung [51] used the AHP to study the planning elements of sustainable urban renewal in Dubai, and Wang et al. [35] used the UAHP to evaluate the possibility of human error in the fracturing process in drilling operations. The key step of the UAHP is the pairwise comparison of specific items (evaluation indexes) in the same layer to calibrate their relative importance. The comparison results are usually determined using SAATY's "1–9" scale approach [52] based on experts' scoring, which can be expressed as an interval number:

$$I_{ij} = \left[p_{ij},\ q_{ij}\right] \tag{2}$$

The interval number $I_{ij}$ represents that the importance of the $j$-th object relative to the $i$-th object is between $p_{ij}$ and $q_{ij}$, where $p$ and $q$ are the adjacent integers according to the "1–9" scale approach.

In this study, it is used to calibrate the relative importance of PA-oriented indexes, which could assess which factor is more positive to the promotion of physical activities in subjective knowledge. And the final relative importance interval number judgment matrix of all the indexes is constructed by the median judgment matrix from multiple experts' scores. Since the interval number judgment matrix obtained by the UAHP cannot obtain the specific weight value, the concept of the deviation degree is therefore introduced into interval numbers to search the potential optimal subjective weights for subsequent evaluation.

Based on the deviation degree, the interval numbers are set to $I_1 = [p_1,\ q_1]$ and $I_2 = [p_2, q_2]$, and the deviation degree $D\ (I_1, I_2)$ can be obtained by Equation (3):

$$D(I_1, I_2) = \sqrt{(p_1 - p_2)^2 + (q_1 - q_2)^2} \tag{3}$$

The larger $D$ is, the greater the deviation degree between interval numbers $I_1$ and $I_2$. The corresponding optimization model for determining the optimal value of interval weights is as follows:

$$\begin{aligned} &\min F(w_n) = \sum_{i=1}^{n}\sum_{j=1}^{n} D^2\left(I_{ij}, W_{ij}\right) = \sum_{i=1}^{n}\sum_{j=1}^{n} D^2\left(I_{ij}, w_i/w_j\right) \\ &s.t.\begin{cases} 0 < w_i \le 1, i = 1, 2, \cdots, n \\ \sum_{i=1}^{n} w_i = 1 \end{cases} \\ &D\left(I_{ij}, w_i/w_j\right) = \sqrt{\left(p_{ij} - w_i/w_j\right)^2 + \left(q_{ij} - w_i/w_j\right)^2} \end{aligned} \tag{4}$$

where *wn* is the optimal subjective weight of each index, *Wij* is the judgment range of the importance of index *i* and *j*, *wi* is the optimal subjective weight of index *i*, and *wj* is the optimal subjective weight of index *j*.

To solve the above model accurately and quickly, the solution of the model is realized by the Genetic Algorithm in this study. The Genetic Algorithm (GA) is an efficient, parallel heuristic global optimization algorithm inspired by biological evolution [53]. The Genetic Algorithm, with its impressive versatility, advanced evolution, and widespread practicality, has emerged as the preeminent methodology for tackling intricate models. Its exceptional capability to optimize search operations within the solution space leads to successive approximations of the optimum solution. Consequently, it streamlines the quest for the

optimal solution by adapting and enhancing the search process. The GA-toolkit built in MATLAB R2021b is employed for the calculation in this paper. The process of solving the optimal subjective weight of the UAHP based on GA is as follows:

1. Construct the objective function and adopt the above formula as the fitness function of the GA.

$$\begin{aligned} & f(X_P) = \sum_{i=1}^{n} \sum_{j=1}^{n} D^2\left(I_{ij}, W_{ij}\right) = \sum_{i=1}^{n} \sum_{j=1}^{n} D^2\left(I_{ij}, w_i/w_j\right) \\ & X_P = [w_1, w_2, \cdots, w_n] \\ & s.t. \begin{cases} 0 < w_i \leq 1, i = 1, 2, \cdots, n \\ \sum_{i=1}^{n} w_i = 1 \end{cases} \end{aligned} \tag{5}$$

2. Solve the optimal subjective weight.

The fitness function calculates the fitness values for all corresponding objective functions in each generation, enabling the selection of an optimal solution for the population. As the population continues to evolve towards the final generation, the optimal fitness value for the objective function becomes the global optimal value, and the corresponding parameter or solution vector wbest represents the optimal subjective weights' value for the interval number judgment matrix.

$$X_{P,n} = \begin{bmatrix} w_{1,1} & w_{1,2} & \cdots & w_{1,n-1} & w_{1,n} \\ w_{2,1} & w_{2,2} & \cdots & w_{2,n-1} & w_{2,n} \\ \vdots & \vdots & & \ddots \ \vdots & \vdots \\ w_{p,1} & w_{p,2} & \cdots & w_{p,n-1} & w_{p,n} \end{bmatrix} \tag{6}$$

where $P$ is the population size generated in each generation, and $X_i = [w_1, w_2, \ldots, w_n]$ is the solution vector of each individual represented in the solution space.

This study has categorized the UGS evaluation indexes based on the aspects mentioned in Section 3.2, taking into account the theme/target layer (A), the primary indexes layer (B), and the secondary indexes layer (C) as the hierarchical structure of the index system. The details of the hierarchical structure for these evaluation indexes can be viewed in Table 8 below. Layer A contains the main objectives of this study and thus determines the quality of the green space overall.

**Table 8.** Hierarchical structure of evaluation indexes.

| Primarily Index Layer B | | Secondary Index Layer C | | Description of each Index |
|---|---|---|---|---|
| B1 | Aesthetics and attractions | C1 | Plant/flower | Plant and flower cover |
| | | C2 | Mountain/hill | Mountain and hill in view |
| | | C3 | River/lake | River and lake in view |
| | | C4 | Water | Water in view |
| B2 | Nature world experience | C5 | Tree cover | Tree cover in view |
| | | C6 | Grass cover | Grass cover in view |
| | | C7 | Land cover | Dirt track, stone, and land in view |
| B3 | Nature conservation | C8 | GR | Area covered by green space |
| | | C9 | GVI | Green Visual Index |
| | | C10 | Amount of rare species | Amount of rare species |
| B4 | Encouraging physical activity | C11 | Residents' participation in PA | The number of times residents participated in PAs |
| | | C12 | Outdoor activities | Total mileage of physical activities |
| | | C13 | Sports diversity | Simpson's diversity index |
| | | C14 | Difficulty of PA | Ratio of road climb height to length |
| B5 | Cultural sector | C15 | Cultural relics protection units | Number of cultural relics protection units |
| | | C16 | Educational value | The number of publications with the keyword |
| B6 | Social sector | C17 | Accessibility (Mean) | The average of the accessibility of the area |
| | | C18 | Accessibility (Max) | The maximum of the accessibility of the area |
| | | C19 | Accessibility (Min) | The minimum of the accessibility of the area |

3.2.2. Entropy Weight Method

The Entropy Weight Method (EWM) evaluates the level of disorder in the index system by analyzing the information entropy value of each index. The higher the entropy value of the assessment index, the lesser the dispersion among the indexes, revealing the insignificant impact of the index in a comprehensive evaluation and a smaller weighting [54]. When dealing with the problem of multi-index weighting, EWM has the capability of eliminating the result deviation caused by subjective evaluation and improving the objectivity and accuracy of evaluation results. In this study, the assignment method was utilized to carry out unified dimensionless quantization of each index at first. Then, the Entropy Weight Method was used to obtain a more objective index weight after quantization. The main calculation steps of the EWM are as follows:

1. Build a dimensionless initial matrix:

$$Y = \left[y_{ij}\right]_{m \times n} \tag{7}$$

where $m$ is the number of objects intended to be evaluated, $n$ is the number of evaluation indexes, and $y_{ij}$ needs to be processed in a dimensionless way.

2. Calculate the information entropy $S_j$ of the $j$-th index:

$$\begin{cases} S_j = -\frac{1}{\ln m} \sum_{i=1}^{m} v_{ij},\ v_{ij} > 0 \\ S_j = 0, \quad v_{ij} = 0 \end{cases} \tag{8}$$

where $v_{ij}$ is the proportion of the $j$-th index of the $i$-th evaluation object.

3. Calculate the objective weight $w_j$ of the $j$-th index:

$$w_j = \frac{1 - S_j}{\sum_{j=1}^{n} (1 - S_j)} \tag{9}$$

3.2.3. Weight Optimization: Improved Combination Weighting Method of Game Theory

In this paper, the UAHP method is employed to assess the significance of indexes based on expert opinions, which establishes the subjective weight of these indexes. Conversely, the EWM computes the entropy value of indexes by assessing their impact on the entirety, thereby determining their objective weights. There could potentially exist disparities between the outcomes acquired by two methods, and relying solely on a single method for assessment indexes would be biased or inadequate. Therefore, it is necessary to find an appropriate approach to recalculate the weights based on the computed subjective and objective weights, enabling the attainment of the comprehensive weights of indexes.

Game theory is an important subject of operations research. The combinatorial weighting method based on game theory can optimize the index weights calculated by the subjective and the objective weighting method to minimize their deviation, thereby achieving the optimal combination of index weights. However, the weight coefficients derived through the principles of game theory may hold a negative value occasionally. In such instances, the outcome is misguided and at odds with actuality. Therefore, the Improved Combination Weighting Method of Game Theory (ICWGT) [55] is used in this paper to correct the coefficients.

The combinatorial weighting based on game theory can be expressed as follows:

$$w = \sum_{l=1}^{L} \alpha_l w_l^T \tag{10}$$

where $\alpha_l$ is the linear combination coefficient, $\alpha_l > 0$; $w$ is the combined weight vector; and $w_l$ is the weight obtained by the $l$-th weighting method. $L$ is the total counts of used weighting methods. ICWGT solves the optimization model by establishing the objective function and adding the constraint conditions of the combination coefficients. With the goal of minimizing the deviation of $w$ and all of the $w_l$ and ensuring that the linear combination coefficients $\alpha_l$ are always positive, the optimized model is as follows:

$$\begin{aligned} &\min_{\alpha_1 \cdots \alpha_L} f = \sum_{i=1}^{L} \left| \left( \sum_{p=1}^{L} \alpha_p w_i w_p^T \right) - w_i w_i^T \right| \\ &s.t. \alpha_p > 0, p = 1, 2, \cdots, L, \sum_{p=1}^{L} \alpha_p^2 = 1 \end{aligned} \tag{11}$$

The model was tackled using the Lagrange function for its components, with partial derivatives employed to derive the finally corrected coefficients. Following this, a normalization process was implemented. The final weight coefficient for the ICWGT combination was determined as follows:

$$\alpha_p^* = \frac{\sum_{i=1}^{L} w_i w_p^T}{\sum_{p=1}^{L} \sum_{i=1}^{L} w_i w_p^T} \tag{12}$$

After correcting the weight coefficients, the comprehensive weight of each evaluation index in the criterion layer (secondary layer) can be further obtained following Equation (10).

## 4. Results and Discussion

### *4.1. Result of Subjective Weights*

By comparing the subjective weights of the primary indexes and the secondary indexes, it is possible to investigate which factors have the most significant impact on the phenomenon from the subjective perspectives of professionals. Therefore, the UAHP method was utilized to assess the appeal of UGSs based on their potential contribution towards the recreational wellness of the visitors. The results are shown in Table 9. In this context, the relative weights of secondary indexes (C) were determined within the same framework of corresponding primary indexes (B) firstly. And the relative weights were further normalized to indicate their relative importance among the total secondary indexes.

It can be seen from the results that, in terms of primary indexes, "encouraging physical activities" occupies the largest weight, followed by the "social value" and "aesthetic and attractions". It is basically consistent with the previous research results [51], which highlighted the importance of sports fields and landscape value for UGSs. As our research primarily focuses on the impact of UGSs on residents' physical activity, the degree to which residents engage in exercise by visiting these areas and the convenience of accessing green spaces are relatively more crucial in subjective cognition. This also explains why the subjective weight of "encouraging physical activity" and "social value" is significantly higher than other indexes. The relatively higher ranking of "aesthetic and attractions" suggests that the quality of greenery itself holds stronger appeal for residents to visit, in comparison to other factors of natural environment such as greenery ratio and coverage of grass and trees.

When it comes to the secondary indexes, it appears that mountains hold a greater significance for green spaces in the perspective of individuals. This contribution could be correlated with the fact that Changsha City is located amidst hilly terrain with an abundance of mountains. The extent of grass coverage makes a contribution of over fifty percent towards the "natural world experience", perhaps owing to the fact that the presence of grassland renders it easier for residents to engage in related physical activities. In terms of "culture value", the emphasis placed on the number of heritage conservation units far

outweighs that of their research value. This clearly indicates that tangible cultural heritage is more closely intertwined with the lives of residents, underscoring the need to prioritize the conservation value of cultural heritage in urban development. For the accessibility of green spaces, the average and maximum time cost for residents to reach green space have the greatest impact on their decisions.

**Table 9.** The optimal subjective weights of indexes obtained by UAHP.

| B | GA-Optimized Weight of Primary Index | Rank | C | Relative Weight | Normalized Weight of Secondary Index | Rank |
|---|---|---|---|---|---|---|
| B1 | 0.199 | 3 | C1 | 0.154 | 0.031 | 15 |
| | | | C2 | 0.344 | 0.069 | 6 |
| | | | C3 | 0.218 | 0.043 | 10 |
| | | | C4 | 0.282 | 0.056 | 8 |
| B2 | 0.106 | 5 | C5 | 0.289 | 0.031 | 16 |
| | | | C6 | 0.562 | 0.060 | 7 |
| | | | C7 | 0.148 | 0.016 | 19 |
| B3 | 0.102 | 6 | C8 | 0.417 | 0.042 | 11 |
| | | | C9 | 0.417 | 0.042 | 12 |
| | | | C10 | 0.167 | 0.017 | 18 |
| B4 | 0.266 | 1 | C11 | 0.359 | 0.095 | 1 |
| | | | C12 | 0.205 | 0.055 | 9 |
| | | | C13 | 0.278 | 0.074 | 5 |
| | | | C14 | 0.159 | 0.042 | 13 |
| B5 | 0.122 | 4 | C15 | 0.778 | 0.095 | 2 |
| | | | C16 | 0.222 | 0.027 | 17 |
| B6 | 0.206 | 2 | C17 | 0.448 | 0.092 | 3 |
| | | | C18 | 0.384 | 0.079 | 4 |
| | | | C19 | 0.168 | 0.035 | 14 |

### *4.2. Results of Objective Weights*

Besides subjective perspectives, objective analysis was conducted through the collected data (refer to Section 3). The objective weights of each index obtained by the EWM are presented in Table 10.

**Table 10.** The objective weights of indexes obtained by the EWM.

| B | Objective Weight of Primary Index | Rank | C | Relative Weight | Normalized Weight of Secondary Index | Rank |
|---|---|---|---|---|---|---|
| B1 | 0.216 | 1 | C1 | 0.236 | 0.051 | 9 |
| | | | C2 | 0.201 | 0.043 | 15 |
| | | | C3 | 0.292 | 0.063 | 4 |
| | | | C4 | 0.271 | 0.059 | 7 |
| B2 | 0.154 | 4 | C5 | 0.325 | 0.050 | 10 |
| | | | C6 | 0.404 | 0.062 | 5 |
| | | | C7 | 0.271 | 0.042 | 18 |
| B3 | 0.136 | 5 | C8 | 0.323 | 0.044 | 14 |
| | | | C9 | 0.320 | 0.043 | 16 |
| | | | C10 | 0.357 | 0.048 | 12 |
| B4 | 0.212 | 2 | C11 | 0.172 | 0.037 | 19 |
| | | | C12 | 0.223 | 0.047 | 13 |
| | | | C13 | 0.280 | 0.060 | 6 |
| | | | C14 | 0.324 | 0.069 | 2 |
| B5 | 0.119 | 6 | C15 | 0.582 | 0.069 | 1 |
| | | | C16 | 0.418 | 0.050 | 11 |
| B6 | 0.162 | 3 | C17 | 0.418 | 0.068 | 3 |
| | | | C18 | 0.259 | 0.042 | 17 |
| | | | C19 | 0.323 | 0.052 | 8 |

The findings indicate that the top three influencing factors are "aesthetic and attractions", "encouraging physical activity", and the "social value", which is consistent with the ranking of those obtained by the UAHP but slightly different in the weights' value. When it comes to each secondary index, factors such as the level of difficulty in sports activities, the quantity of cultural heritage sites, and the average accessibility of green spaces hold a correspondingly greater weight compared to other indexes. For landscaping, we have observed that rivers/lakes hold the highest importance among all the landscaping elements. This aligns with the outcomes of prior research [56], indicating that green spaces in proximity to water bodies possess greater value than other types of green areas.

### *4.3. Comparisons of the Results*

Based on the above results, it can be seen that there are still some subjective and objective cognitive biases regarding the relative importance of influencing factors. Thus, this study hopes to adjust the difference in subjective and objective understanding and then obtain more comprehensive, objective, and reasonable weights for evaluation analysis. According to the ICWGT method shown in Section 3.2.3, the combined weight coefficients of the subjective weight and objective weight are $\alpha_S = 0.50564$ and $\alpha_O = 0.49436$, respectively, while the comprehensive weights of primary indexes and secondary indexes are shown in Tables 11 and 12:

**Table 11.** The comprehensive weight of primary indexes.

| B | GA-Optimized Subjective Weight | Rank | Objective Weight | Rank | Comprehensive Weight | Rank |
|---|---|---|---|---|---|---|
| B1 | 0.187 | 3 | 0.216 | 1 | 0.202 | 2 |
| B2 | 0.141 | 5 | 0.154 | 4 | 0.148 | 4 |
| B3 | 0.100 | 6 | 0.136 | 5 | 0.118 | 6 |
| B4 | 0.250 | 1 | 0.212 | 2 | 0.231 | 1 |
| B5 | 0.117 | 4 | 0.119 | 6 | 0.118 | 5 |
| B6 | 0.203 | 2 | 0.162 | 3 | 0.183 | 3 |

**Table 12.** The comprehensive weight of secondary indexes.

| C | Subjective Weight | Rank | Objective Weight | Rank | Comprehensive Weight | Rank |
|---|---|---|---|---|---|---|
| C1 | 0.069 | 15 | 0.051 | 9 | 0.060 | 7 |
| C2 | 0.031 | 6 | 0.043 | 15 | 0.037 | 16 |
| C3 | 0.044 | 10 | 0.063 | 4 | 0.053 | 9 |
| C4 | 0.056 | 8 | 0.059 | 7 | 0.057 | 8 |
| C5 | 0.031 | 16 | 0.050 | 10 | 0.040 | 14 |
| C6 | 0.060 | 7 | 0.062 | 5 | 0.061 | 5 |
| C7 | 0.016 | 19 | 0.042 | 18 | 0.029 | 19 |
| C8 | 0.023 | 11 | 0.044 | 14 | 0.033 | 18 |
| C9 | 0.057 | 12 | 0.043 | 16 | 0.050 | 12 |
| C10 | 0.023 | 18 | 0.048 | 12 | 0.035 | 17 |
| C11 | 0.066 | 1 | 0.037 | 19 | 0.051 | 11 |
| C12 | 0.082 | 9 | 0.047 | 13 | 0.065 | 4 |
| C13 | 0.082 | 5 | 0.060 | 6 | 0.071 | 3 |
| C14 | 0.035 | 13 | 0.069 | 2 | 0.052 | 10 |
| C15 | 0.095 | 2 | 0.069 | 1 | 0.082 | 1 |
| C16 | 0.027 | 17 | 0.050 | 11 | 0.038 | 15 |
| C17 | 0.092 | 3 | 0.068 | 3 | 0.080 | 2 |
| C18 | 0.079 | 4 | 0.042 | 17 | 0.061 | 5 |
| C19 | 0.035 | 14 | 0.052 | 8 | 0.043 | 13 |

Comparative analysis was performed on the subjective weight obtained from the UAHP method, the objective weight obtained from the EWM, and the combined weight

obtained from the ICWGT. The results are presented in a visual format in the following Figures 7 and 8:

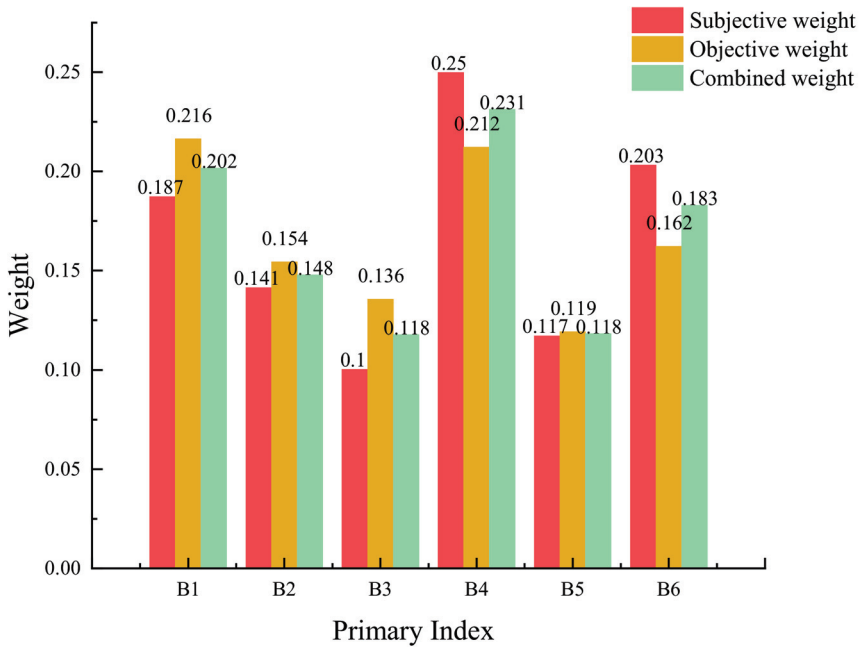



**Figure 7.** The comparison of obtained weights of primary indexes.

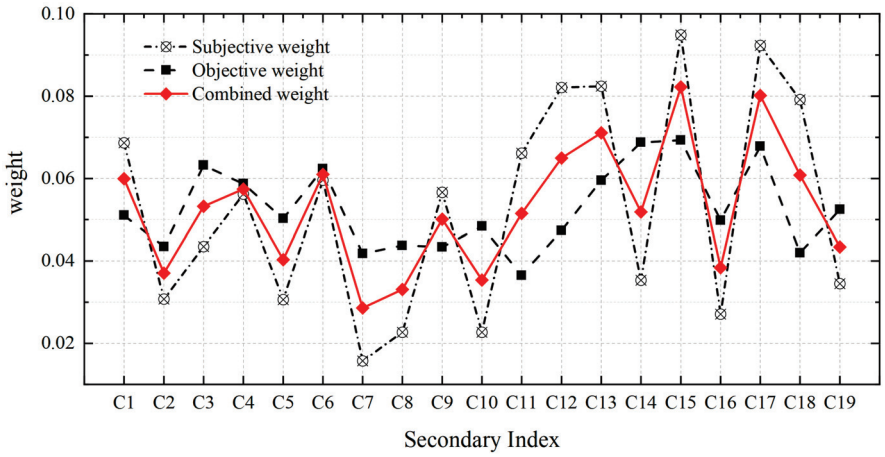



**Figure 8.** The comparison of obtained weights of secondary indexes.

In Figure 8, the volatility in outcomes derived from subjective weighting in specific project metrics significantly surpasses that of objective weighting. This could be attributed to experts exhibiting notable preferences when scoring certain metric items within the range, thereby resulting in considerable fluctuations in the final outcomes. And it has been found that all of the comprehensive weights by optimized ICWGT lie between the subjective weights and the objective weights. This suggests that an effective balance between subjective evaluation and objective evaluation has been found in the results, by which the subjective nature of UAHP index evaluation has been effectively reduced, while the accuracy of the results has been enhanced through objective statistics.

It can be concluded that "encouraging physical activity" has the greatest weight in all the standard levels. In other words, whether the surrounding inhabitants can voluntarily visit the green space and carry out a series of activities is an important factor in evaluating UGSs when it comes to promoting residents' movement. In the context of policy initiatives like the "National Fitness Campaign" and the promotion of "Healthy Cities", enhancing

and refining the sporting facilities within UGSs, such as running tracks and bike lanes, can significantly encourage nearby residents to independently engage in physical activities in these areas. The combined weight of "aesthetics and attractions" ranks second in the results, which indicates that the quality of the UGS landscape structure itself plays an important role in the whole evaluation system. Studies have shown that low-intensity activities (such as strolling and sightseeing) are the most common activities for surrounding people when visiting green spaces [57]. That is, individuals are more willing to go to scenic and ornamental green space for low-intensity activities. The third criterion on the list is the "social value", indicating that green spaces in cities with higher accessibility are more popular among people, and it also means that accessibility is not the primary factor that determines or inhibits the residents from engaging in physical activities in UGSs. The remaining three indexes, namely, "nature world experience", "cultural sector", and "nature conservation", occupy the fourth and joint-fifth positions. Although the influence of vegetation coverage, cultural value, and natural conservation on the assessment is lesser than that of the previous three, their effects regarding citizens' physical activities are still not negligible.

Regarding secondary indexes, it is noteworthy that the category "cultural relics protection units" boasts the highest composite weight value. This could stem from the fact that its subjective evaluation carries more weight than the educational significance within the same category. The specific metrics that closely follow the ranking are the "mean value of accessibility" and "sports diversity", reflecting the extent of accessibility to UGSs and the suitability of these spaces for a variety of activities, both of which play a significant role in the evaluation system. The above findings offer valuable insights for urban green space designs and development. While ensuring the cultural significance and aesthetic quality of green areas, incorporating facilities that encourage physical activity can effectively encourage residents to utilize these spaces.

### *4.4. Discussion*

The aim of this research is to investigate an applicable and comprehensive assessment framework for UGSs with physical activity as a mediator to enhance the health and well-being of inhabitants living near these spaces. This initiative seeks to compensate for the inadequacies of hitherto UGS planning, which has predominantly focused on policy considerations. By improving the design and planning of UGSs, especially with regards to the physical and mental well-being of inhabitants, the results of this research can be leveraged to provide valuable insights into urban renewal, old city reconstruction, and optimization of green space landscapes.

The highlight of this paper lies in its comprehensive assessment process of UGSs, achieved by blending subjective and objective evaluation techniques. By employing the ICWGT method, this paper derives the holistic weighting of these indexes, effectively mitigating the potential distortion of data accuracy caused by single subjective evaluations. Departing from conventional questionnaire methodologies, this paper opts for a more resident-centric approach in selecting and procuring methods and data. It delves into diverse metrics intimately linked to residents' daily lives, including the distribution of green landscapes, the accessibility of green spaces, and residents' mobility patterns. The research methodology employed in this paper offers a more concrete depiction of how the varying quality levels of UGSs impact the daily transportation routines of inhabitants by offering them spaces for outdoor physical activities.

On the other hand, this paper innovates in the objective evaluation of UGSs from multiple perspectives. Using semantic segmentation technology, this research explores the aesthetic and experiential benefits of green spaces. Quantitative analysis is conducted on central network images obtained through the data mining method. Since the majority of photographs on social media platforms depict landscapes from a human viewpoint, they are inadequate representations of the overall structure of green spaces. Nevertheless, this study focuses on the way individuals use green spaces, and the proportions of landscape

elements visible to people accurately convey the impact the surroundings have on their users. This study employs sports data from Keep® software to gauge the physical activity value of green spaces, thereby providing substantial backing for the development of an urban green space evaluation model, with a distinct emphasis on sports-centric aspects.

However, in terms of the conservation significance of natural spaces during evaluation, while utilizing GA, GVI, and the diversity of plant species as evaluative benchmarks can partly gauge the conservation merit of green spaces, this overlooks the diversity and safeguarding status of animal species, and the data parameters may not be exhaustive. Given this paper's emphasis on assessing the influence of nearby residents' physical activity on the UGS evaluation framework, the accessibility of green spaces is solely investigated based on pedestrian accessibility, without considerations for vehicular access to these spaces.

## 5. Conclusions and Suggestions

Based on the proposed evaluation system of UGSs, this paper uses UAHP, EWM, and ICWGT to calculate the combined weights of various evaluation dimensions of green space from the perspective of residents' physical activity and puts forward a novel UGS assessment approach aimed at providing scientific reference for the construction, urban renewal, and transformation of eco-cities and healthy cities.

During the assessment phase, the interval numbers of the UAHP were employed to gauge the significance of indexes, incorporating the deviation degree model and GA for the weights' computation. By delineating the degree of contribution of each index to the final evaluation through the EWM, the objective weights of indexes were quantitatively determined based on the collected data. Finally, the Improved Combined Method of Game Theory (ICWGT) has the capability to combine the outcomes of both subjective and objective evaluations, culminating in more precise and scientifically grounded combined weights for comprehensive evaluation.

Overall, based on the forementioned findings, it was concluded that when evaluating urban green spaces with a focus on the residents' physical activities, residents' engagement in physical activities within green spaces (B4) holds the greatest weight in the overall evaluation index system. In other words, green spaces have a greater appeal to the surrounding residents when they contain suitable sports facilities that meet their needs. Facilities for reference include plastic running or walking tracks, cycling paths, children's play facilities and venues [58], etc. The landscape quality (B1) and accessibility (B6) of green spaces also have a great impact on the evaluation system of UGSs, which is similar to the previous study by Zhang et al. [57]. This suggests that it is important for urban planners to prioritize the enhancement of the linkage between green spaces and residential zones. This involves improving the systematic planning and administration of these green areas and maximizing their capacity to encourage physical activities, enhancing environmental qualities, and fortifying the overall physical and mental welfare of residents. The adoption of such strategies would empower municipal authorities to develop urban areas that are not only more conducive to living but also more dynamic and prosperous.

**Author Contributions:** Conceptualization, T.D. and C.F.; methodology, T.D. and C.F.; software, C.F. and Z.Z.; validation, C.F., B.Y. and Z.Z.; formal analysis, C.F.; investigation, C.F. and B.Y.; resources, T.D.; data curation, C.F.; writing—original draft preparation, T.D.; writing—review and editing, T.D. and C.F.; visualization, C.F., B.Y., and Z.Z.; funding acquisition, T.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Humanities and Social Sciences Youth Foundation, Ministry of Education of the People's Republic of China. Title: Research on typical urban green space landscape design method based on the relationship between ecosystem cultural services and residents' health. Grant number: 23YJCZH039.

**Data Availability Statement:** Dataset available on request from the authors.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References


1. Kondo, M.C.; Fluehr, J.M.; McKeon, T.; Branas, C.C. Urban Green Space and Its Impact on Human Health. *Int. J. Environ. Res. Public Health* **2018**, *15*, 445. [CrossRef] [PubMed]
2. van Dillen, S.M.E.; de Vries, S.; Groenewegen, P.P.; Spreeuwenberg, P. Greenspace in urban neighbourhoods and residents' health: Adding quality to quantity. *J. Epidemiol. Community Health* **2012**, *66*, e8. [CrossRef] [PubMed]
3. Bixby, H.; Hodgson, S.; Fortunato, L.; Hansell, A.; Fecht, D. Associations between Green Space and Health in English Cities: An Ecological, Cross-Sectional Study. *PLoS ONE* **2015**, *10*, e0119495. [CrossRef] [PubMed]
4. Farkas, J.Z.; Hoyk, E.; de Morais, M.B.; Csomós, G. A systematic review of urban green space research over the last 30 years: A bibliometric analysis. *Heliyon* **2023**, *9*, e13406. [CrossRef] [PubMed]
5. Hedblom, M.; Gunnarsson, B.; Iravani, B.; Knez, I.; Schaefer, M.; Thorsson, P.; Lundström, J.N. Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Sci. Rep.* **2019**, *9*, 10113. [CrossRef] [PubMed]
6. Li, Q.; Liu, Y.; Yang, L.; Ge, J.; Chang, X.; Zhang, X. The impact of urban green space on the health of middle-aged and older adults. *Front. Public Health* **2023**, *11*, 1244477. [CrossRef]
7. Firth, J.; Solmi, M.; Wootton, R.E.; Vancampfort, D.; Schuch, F.B.; Hoare, E.; Gilbody, S.; Torous, J.; Teasdale, S.B.; Jackson, S.E.; et al. A meta-review of "lifestyle psychiatry": The role of exercise, smoking, diet and sleep in the prevention and treatment of mental disorders. *World Psychiatry* **2020**, *19*, 360–380. [CrossRef] [PubMed]
8. Zhou, R.; Zheng, Y.-J.; Yun, J.-Y.; Wang, H.-M. The Effects of Urban Green Space on Depressive Symptoms of Mid-Aged and Elderly Urban Residents in China: Evidence from the China Health and Retirement Longitudinal Study. *Int. J. Environ. Res. Public Health* **2022**, *19*, 717. [CrossRef] [PubMed]
9. Vella, S.A.; Aidman, E.; Teychenne, M.; Smith, J.J.; Swann, C.; Rosenbaum, S.; White, R.L.; Lubans, D.R. Optimising the effects of physical activity on mental health and wellbeing: A joint consensus statement from Sports Medicine Australia and the Australian Psychological Society. *J. Sci. Med. Sport* **2023**, *26*, 132–139. [CrossRef]
10. Wolch, J.R.; Byrne, J.; Newell, J.P. Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landsc. Urban Plan.* **2014**, *125*, 234–244. [CrossRef]
11. Zheng, Y.; Cheng, B.; Dong, L.; Zheng, T.; Wu, R. The Moderating Effect of Social Participation on the Relationship between Urban Green Space and the Mental Health of Older Adults: A Case Study in China. *Land* **2024**, *13*, 317. [CrossRef]
12. Reyes-Riveros, R.; Altamirano, A.; De la Barrera, F.; Rozas-Vasquez, D.; Vieli, L.; Meli, P. Linking public urban green spaces and human well-being: A systematic review. *Urban For. Urban Green.* **2021**, *61*, 127105. [CrossRef]
13. Lee, C.; Kim, H.J.; Dowdy, D.M.; Hoelscher, D.M.; Ory, M.G. TCOPPE School Environmental Audit Tool: Assessing Safety and Walkability of School Environments. *J. Phys. Act. Health* **2013**, *10*, 949–960. [CrossRef] [PubMed]
14. Rigolon, A. Parks and young people: An environmental justice study of park proximity, acreage, and quality in Denver, Colorado. *Landsc. Urban Plan.* **2017**, *165*, 73–83. [CrossRef]
15. Zhang, Z.; Xu, C.; Gong, L.; Cai, B.; Li, C.; Huang, G.; Li, B. Assessment on structural quality of landscapes in green space of Beijing suburban parks by SBE method. *Sci. Silvae Sin.* **2011**, *47*, 53–60. [CrossRef]
16. Song, Y.; Xu, S.; Liu, Z.; Zhang, Y.; Qiu, P.; Niu, A.; Xu, G. Time and space differences of water environmental quality of the mangrove wetland park in Nansha: Based on the improved twice-slope clustering method. *Sci. Geogr. Sin.* **2016**, *36*, 303–311. [CrossRef]
17. Xu, H.; Li, Q. Analysis of the Evaluative Dimensions and Causal Relationship on Theme Park Visitors' Experience Quality: Based on a C-trip Comments Review of Disney and Happy Valley. *Tour. Sci.* **2017**, *31*, 57–68. [CrossRef]
18. Xiao, N.; Huang, Y.; Liu, J.S. Evaluation and spatial differentiation of tourism experience quality of theme park in China. *Sci. Geogr. Sin.* **2019**, *39*, 978–986. (In Chinese) [CrossRef]
19. Markevych, I.; Schoierer, J.; Hartig, T.; Chudnovsky, A.; Hystad, P.; Dzhambov, A.M.; de Vries, S.; Triguero-Mas, M.; Brauer, M.; Nieuwenhuijsen, M.J.; et al. Exploring pathways linking greenspace to health: Theoretical and methodological guidance. *Environ. Res.* **2017**, *158*, 301–317. [CrossRef] [PubMed]
20. Lepczyk, C.A.; Aronson, M.F.J.; Evans, K.L.; Goddard, M.A.; Lerman, S.B.; MacIvor, J.S. Biodiversity in the City: Fundamental Questions for Understanding the Ecology of Urban Green Spaces for Biodiversity Conservation. *BioScience* **2017**, *67*, 799–807. [CrossRef]
21. Zhao, X.; Li, F.; Yan, Y.; Zhang, Q. Biodiversity in Urban Green Space: A Bibliometric Review on the Current Research Field and Its Prospects. *Int. J. Environ. Res. Public Health* **2022**, *19*, 12544. [CrossRef] [PubMed]
22. Macintyre, V.G.; Cotterill, S.; Anderson, J.; Phillipson, C.; Benton, J.S.; French, D.P. "I Would Never Come Here Because I've Got My Own Garden": Older Adults' Perceptions of Small Urban Green Spaces. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1994. [CrossRef] [PubMed]
23. Lengen, C. The effects of colours, shapes and boundaries of landscapes on perception, emotion and mentalising processes promoting health and well-being. *Health Place* **2015**, *35*, 166–177. [CrossRef]
24. Jennings, V.; Bamkole, O. The Relationship between Social Cohesion and Urban Green Space: An Avenue for Health Promotion. *Int. J. Environ. Res. Public Health* **2019**, *16*, 452. [CrossRef] [PubMed]
25. Chuang, Y.-C.; Chuang, K.-Y.; Yang, T.-H. Social cohesion matters in health. *Int. J. Equity Health* **2013**, *12*, 87. [CrossRef] [PubMed]
26. McCormack, G.R.; Rock, M.; Toohey, A.M.; Hignell, D. Characteristics of urban parks associated with park use and physical activity: A review of qualitative research. *Health Place* **2010**, *16*, 712–726. [CrossRef] [PubMed]

27. Li, L.; Zheng, Y.; Ma, S. Links of urban green space on environmental satisfaction: A spatial and temporarily varying approach. *Environ. Dev. Sustain.* **2023**, *25*, 3469–3501. [CrossRef]
28. Tian, D.; Wang, J.; Xia, C.; Zhang, J.; Zhou, J.; Tian, Z.; Zhao, J.; Li, B.; Zhou, C. The relationship between green space accessibility by multiple travel modes and housing prices: A case study of Beijing. *Cities* **2024**, *145*, 104694. [CrossRef]
29. World Health Organization. *Urban Green Spaces and Health*; WHO Regional Office for Europe: Copenhagen, Denmark, 2016. Available online: https://iris.who.int/handle/10665/345751 (accessed on 15 March 2023).
30. Schindler, M.; Le Texier, M.; Caruso, G. How far do people travel to use urban green space? A comparison of three European cities. *Appl. Geogr.* **2022**, *141*, 102673. [CrossRef]
31. Li, X.; Zhang, C.; Li, W.; Ricard, R.; Meng, Q.; Zhang, W. Assessing street-level urban greenery using Google Street View and a modified green view index. *Urban For. Urban Green.* **2015**, *14*, 675–685. [CrossRef]
32. Xia, Y.; Yabuki, N.; Fukuda, T. Development of a system for assessing the quality of urban street-level greenery using street view images and deep learning. *Urban For. Urban Green.* **2021**, *59*, 126995. [CrossRef]
33. Chen, J.; Shao, S.; Zhu, Y.; Wang, Y.; Rao, F.; Dai, X.; Lai, D. Enhanced Automatic Identification of Urban Community Green Space Based on Semantic Segmentation. *Land* **2022**, *11*, 905. [CrossRef]
34. Wang, J.; Liu, W.; Gou, A. Numerical characteristics and spatial distribution of panoramic Street Green View index based on SegNet semantic segmentation in Savannah. *Urban For. Urban Green.* **2022**, *69*, 127488. [CrossRef]
35. Wang, Q.; Zhang, L.; Hu, J. An integrated method of human error likelihood assessment for shale-gas fracturing operations based on SPA and UAHP. *Process. Saf. Environ. Prot.* **2019**, *123*, 105–115. [CrossRef]
36. Madzík, P.; Falát, L. State-of-the-art on analytic hierarchy process in the last 40 years: Literature review based on Latent Dirichlet Allocation topic modelling. *PLoS ONE* **2022**, *17*, e0268777. [CrossRef] [PubMed]
37. Wang, S.; Wu, Y.J.; Li, R. An Improved Genetic Algorithm for Location Allocation Problem with Grey Theory in Public Health Emergencies. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9752. [CrossRef] [PubMed]
38. Qin, Y.; He, J.; Wei, M.; Du, X. Challenges Threatening Agricultural Sustainability in Central Asia: Status and Prospect. *Int. J. Environ. Res. Public Health* **2022**, *19*, 6200. [CrossRef] [PubMed]
39. Lai, C.; Chen, X.; Chen, X.; Wang, Z.; Wu, X.; Zhao, S. A fuzzy comprehensive evaluation model for flood risk based on the combination weight of game theory. *Nat. Hazards* **2015**, *77*, 1243–1259. [CrossRef]
40. Chen, M.-S.; Han, J.; Yu, P. Data mining: An overview from a database perspective. *IEEE Trans. Knowl. Data Eng.* **1996**, *8*, 866–883. [CrossRef]
41. Keeler, B.L.; Wood, S.A.; Polasky, S.; Kling, C.; Filstrup, C.T.; Downing, J.A. Recreational demand for clean water: Evidence from geotagged photographs by visitors to lakes. *Front. Ecol. Environ.* **2015**, *13*, 76–81. [CrossRef] [PubMed]
42. Tenkanen, H.; Di Minin, E.; Heikinheimo, V.; Hausmann, A.; Herbst, M.; Kajala, L.; Toivonen, T. Instagram, Flickr, or Twitter: Assessing the usability of social media data for visitor monitoring in protected areas. *Sci. Rep.* **2017**, *7*, 17615. [CrossRef]
43. LeCun, Y.; Bengio, Y.; Hinton, G. Deep learning. *Nature* **2015**, *521*, 436–444. [CrossRef] [PubMed]
44. Zhou, B.; Zhao, H.; Puig, X.; Fidler, S.; Barriuso, A.; Torralba, A. Scene Parsing through ADE20K Dataset. In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Honolulu, HI, USA, 21–26 July 2017; pp. 5122–5130.
45. Wu, H.; Wang, L.; Zhang, Z.; Gao, J. Analysis and optimization of 15-minute community life circle based on supply and demand matching: A case study of Shanghai. *PLoS ONE* **2021**, *16*, e0256904. [CrossRef] [PubMed]
46. Huang, R.; Liu, Y.; Liang, S.; Si, J.; Di, S.; Cai, M.; Hu, S.; Hao, C.; Zhao, Z. Social Value of Urban Green Space Based on Visitors' Perceptions: The Case of the Summer Palace, Beijing, China. *Forests* **2023**, *14*, 2192. [CrossRef]
47. Knobel, P.; Dadvand, P.; Alonso, L.; Costa, L.; Espanol, M.; Maneja, R. Development of the urban green space quality assessment tool (RECITAL). *Urban For. Urban Green.* **2021**, *57*, 126895. [CrossRef]
48. Stoia, N.L.; Niţă, M.R.; Popa, A.M.; Iojă, I.C. The green walk—An analysis for evaluating the accessibility of urban green spaces. *Urban For. Urban Green.* **2022**, *75*, 11. [CrossRef]
49. Lu, Y.; Chen, R.; Chen, B.; Wu, J. Inclusive green environment for all? An investigation of spatial access equity of urban green space and associated socioeconomic drivers in China. *Landsc. Urban Plan.* **2024**, *241*, 104926. [CrossRef]
50. Yaraghi, N.; Tabesh, P.; Guan, P.; Zhuang, J. Comparison of AHP and Monte Carlo AHP Under Different Levels of Uncertainty. *IEEE Trans. Eng. Manag.* **2015**, *62*, 122–132. [CrossRef]
51. Awad, J.; Jung, C. Extracting the Planning Elements for Sustainable Urban Regeneration in Dubai with AHP (Analytic Hierarchy Process). *Sustain. Cities Soc.* **2022**, *76*, 103496. [CrossRef]
52. Saaty, T.L. The Modern Science of Multicriteria Decision Making and Its Practical Applications: The AHP/ANP Approach. *Oper. Res.* **2013**, *61*, 1101–1118. [CrossRef]
53. Michalewicz, Z.; Schoenauer, M. Evolutionary Algorithms for Constrained Parameter Optimization Problems. *Evol. Comput.* **1996**, *4*, 1–32. [CrossRef]
54. Ren, J.; Xiong, Y. An optimised method of weighting combination in multi-index comprehensive evaluation. *Int. J. Appl. Decis. Sci.* **2010**, *3*, 34–52. [CrossRef]
55. Li, A.H. Research on Safety Assessment Method of Quayside Container Crane. Ph.D. Thesis, Wuhan University of Technology, Wuhan, China, 2017.
56. Zhou, W.; Cao, W.; Wu, T.; Zhang, T. The win-win interaction between integrated blue and green space on urban cooling. *Sci. Total. Environ.* **2023**, *863*, 160712. [CrossRef] [PubMed]

57. Zhang, W.; Yang, J.; Ma, L.; Huang, C. Factors affecting the use of urban green spaces for physical activities: Views of young urban residents in Beijing. *Urban For. Urban Green.* **2015**, *14*, 851–857. [CrossRef]
58. Bao, Y.; Gao, M.; Luo, D.; Zhou, X. Urban Parks—A Catalyst for Activities! The Effect of the Perceived Characteristics of the Urban Park Environment on Children's Physical Activity Levels. *Forests* **2023**, *14*, 423. [CrossRef]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

*Article*

# Combined Effects of the Visual–Acoustic Environment on Public Response in Urban Forests

**Yuxiang Lan [1], Yuanyang Tang [1], Zhanhua Liu [1], Xiong Yao [1], Zhipeng Zhu [1], Fan Liu [2], Junyi Li [2], Jianwen Dong [2] and Ye Chen [2,*]**

[1] College of Architecture and Planning, Fujian University of Technology, Fuzhou 350108, China; 19912325@fjut.edu.cn (Y.L.); 2230812059@smail.fjut.edu.cn (Y.T.); 2230812058@smail.fjut.edu.cn (Z.L.); fjyx@fjut.edu.cn (X.Y.); 19912151@fjut.edu.cn (Z.Z.)

[2] College of Landscape Architecture and Art, Fujian Agriculture and Forestry University, 15 Shangxiadian Rd., Fuzhou 350001, China; 2221775007@fafu.edu.cn (F.L.); 22319075007@fafu.edu.cn (J.L.); fjdjw@fafu.edu.cn (J.D.)

* Correspondence: 2191775001@fafu.edu.cn

**Abstract:** Urban forests are increasingly recognized as vital components of urban ecosystems, offering a plethora of physiological and psychological benefits to residents. However, the existing research has often focused on single dimensions of either visual or auditory experiences, overlooking the combined impact of audio–visual environments on public health and well-being. This study addresses this gap by examining the effects of composite audio–visual settings within three distinct types of urban forests in Fuzhou, China: mountain, mountain–water, and waterfront forests. Through field surveys and quantitative analysis at 24 sample sites, we assessed visual landscape elements, soundscapes, physiological indicators (e.g., heart rate, skin conductance), and psychological responses (e.g., spiritual vitality, stress relief, emotional arousal, attention recovery) among 77 participants. Our findings reveal that different forest types exert varying influences on visitors' physiology and psychology, with waterfront forests generally promoting relaxation and mountain–water forests inducing a higher degree of tension. Specific audio–visual elements, such as plant, water scenes, and natural sounds, positively affect psychological restoration, whereas urban noise is associated with increased physiological stress indicators. In conclusion, the integrated effects of audio–visual landscapes significantly shape the multisensory experiences of the public in urban forests, underscoring the importance of optimal design that incorporates natural elements to create restorative environments beneficial to the health and well-being of urban residents. These insights not only contribute to the scientific understanding of urban forest impact but also inform the design and management of urban green spaces for enhanced public health outcomes.

**Keywords:** urban forests; audio–visual environment; physiological responses; psychological responses; public health; landscape design

**Citation:** Lan, Y.; Tang, Y.; Liu, Z.; Yao, X.; Zhu, Z.; Liu, F.; Li, J.; Dong, J.; Chen, Y. Combined Effects of the Visual–Acoustic Environment on Public Response in Urban Forests. *Forests* **2024**, *15*, 858. https://doi.org/10.3390/f15050858

Academic Editor: Paloma Cariñanos

Received: 22 April 2024
Revised: 11 May 2024
Accepted: 12 May 2024
Published: 14 May 2024
Corrected: 9 July 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Urban forests are invaluable components of city ecosystems, providing urban dwellers with a multitude of physical and psychological health benefits. A growing body of research suggests that the environmental features of urban forests [1], such as vegetation [2], water features [3], and soundscapes [4], can influence individuals' sensory experiences, thereby impacting their health and well-being.

Despite extensive research exploring the relationship between human perception and specific environmental factors in urban forests, investigations into the combined effects of different factors remain limited. Given that recreational activities in forest environments often involve multiple and interactive aspects, examining the influence of individual factors on human perception alone fails to fully capture their real-world experience. Therefore, it is essential to investigate the combined effects of multiple factors on public responses. The existing studies demonstrate that the combined effects of two or more sensory modalities

can produce synergistic effects, either enhancing or diminishing individual experiences. For example, the thermal–acoustic effect (the combined influence of sound and temperature) in urban forests can impact people's comfort levels [5]. Hot environments can induce discomfort, while noise can exacerbate this discomfort. However, an appropriate thermal–acoustic environment can create a more comfortable and pleasant space. For instance, shade trees can reduce perceived temperature, and the sound of fountains or water features can provide a cooling sensation. Furthermore, the interaction of olfactory and auditory stimuli is also evident in urban public open spaces [6]. In gardens, the combination of floral scents and birdsong can create a tranquil and serene atmosphere. Research on audiovisual interactions in indoor environments [7] has also shown that in offices, the visual presence of plants and natural imagery can mitigate the impact of office noise, while background music can aid concentration. In addition, other researchers have found that in campus recreational areas and green spaces, there is a clear relationship between the perception of sounds and well-being. However, in some areas near the water, despite the reported higher noise levels, the respondents felt quite comfortable [8]. By optimizing the audiovisual characteristics of urban forests, we can create more livable and healthy urban environments that promote the physical and mental well-being of residents.

This study aims to address the gap in research on the impact of outdoor visual–acoustic interactions on public response. We selected three different types of urban forests in Fuzhou, China, as our research sites and measured visual environmental elements, auditory environmental elements, and the physiological and psychological responses of participants. Using a combination of deep learning techniques and quantitative analyses, we investigated the effects of visual–acoustic landscape features in different forest settings on the sensory experiences, health, and well-being of the public.

The findings of this study provide scientific evidence to optimize urban forest landscape design and management for promoting the health and well-being of urban residents. Our findings can assist planners, landscape designers, and policymakers in creating more livable and healthy urban environments.

## 2. Materials and Methods

### *2.1. Study Site Overview*

In conducting scientific research, the selection of an appropriate study area is crucial to ensure the validity and reliability of the research findings. This study selects Fuzhou City as the research area. As the capital city of Fujian Province, Fuzhou is not only a pivotal city in the Haixi Economic Zone but also one of China's national historical and cultural cities, and it is at the forefront of economic development [9].

Fuzhou is renowned for its beautiful natural environment and abundant forest tourism resources. Its beautiful natural landscapes and ecological environment have been fully recognized by the state, and it has been successively awarded the honorary titles of "National Garden City" and "Provincial Forest City". These characteristics make Fuzhou an ideal place to study the ecosystem and social functions of urban forests.

After comprehensively considering factors such as the area of urban forests, the number of visitors, and accessibility, this study carefully selected three representative forests as research objects. These three forests are Jinniushan Sports Park (representing mountainous urban forests), Fuzhou National Forest Park (representing mountain and water urban forests), and Xihu Park (representing waterfront urban forests). As shown in Figure 1, these three forests are not only geographically representative but also cover the main types of urban forests, providing a rich comparative basis for the study.

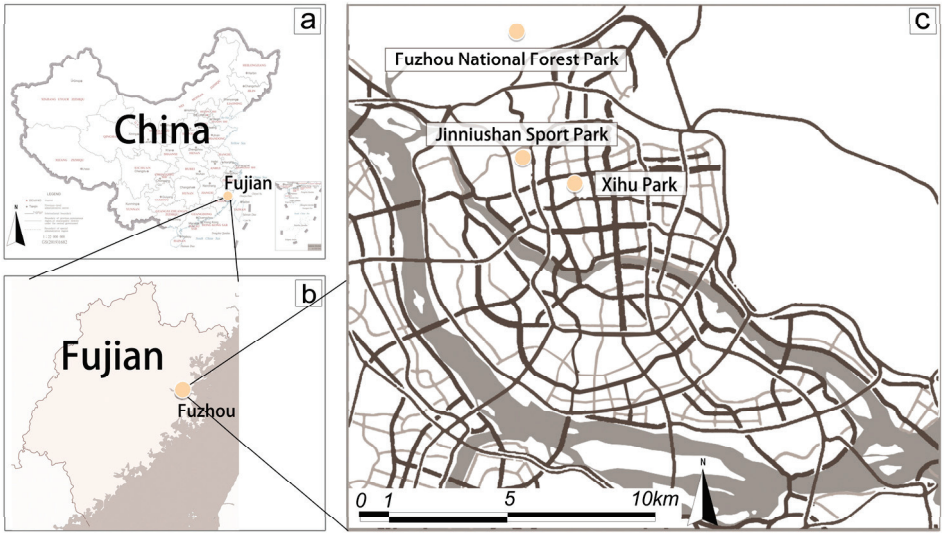



**Figure 1.** (**a**) Location of Fujian Province in map of China; (**b**) Location of Fuzhou City in map of Fujian; (**c**) Study site selection of urban forests in Fuzhou.

### *2.2. Forest Overview and Survey Point Layout*

Table 1 provides an overview of the three urban forests in Fuzhou. Figures 2 and 3 show the position of the sites. The study divides them into 24 sample site scenes. Jinniushan Sports Park has 8 sample sites, denoted as S1–S8. Fuzhou National Forest Park has 9 sample sites, denoted as F1–F9. Xihu Park has 7 sample sites, denoted as X1–X7. Tables 2–4 provide an overview of the 24 sample sites.

**Table 1.** Overview of parks.

| Park Name | Overview |
|---|---|
| Jinniushan Sports Park (Fudao Gate 3) | Characterized by undulating terrain and picturesque scenery, it is the largest community-type semi-hilly sports park in the heart of Fuzhou City and serves as the entrance at Fudao Gate 3. |
| Fuzhou National Forest Park | Fuzhou National Forest Park (also known as "Fuzhou Botanical Garden") is the first national-level forest park in Fujian Province, one of the top ten forest parks in China, and one of the six 4A-level scenic spots in the Fuzhou area. The total planned area spans 2891.3 $hm^2$, with a water catchment area reaching 13 $km^2$. |
| Xihu Park | Located in the northwest part of Gulou District in Fuzhou City, at the heart of the urban area, the current land area is 42.51 $hm^2$, of which the land area is 12.21 $hm^2$, and the water surface area is 30.3 $hm^2$. |

(**a**) (**b**) (**c**)

**Figure 2.** (**a**) Study site selection of Jinniushan Sports Park; (**b**) Study site selection of Fuzhou National Forest Park; (**c**) Study site selection of Xihu Park.

(**a**) (**b**) (**c**)

**Figure 3.** (**a**) Plots of Jinniushan Sports Park; (**b**) Plots of Fuzhou National Forest Park; (**c**) Plots of Xihu Park.

**Table 2.** Overview of Jinniushan Sports Park plot.

| Plot Number | Plot Name | Plot Introduction |
|---|---|---|
| S1 | Entrance Square | Situated at the entrance of Jinniushan Sports Park (Fudao Gate 3), the terrain is level and expansive, with nearby amenities such as KFC, a sports gym, and the Shangfu Road Rotating Walkway. |
| S2 | Mixed Coniferous and Broad-Leaved Forest | Nestled amidst the canopy of the boardwalk, adjacent to aerial resting platforms, the view is sequestered by both broad-leaved and coniferous trees. |
| S3 | Broad-Leaved Forest | Situated along the hiking trail. |
| S4 | Bamboo Forest | Nestled along the hiking trail, the surroundings are dominated by a verdant bamboo forest. |
| S5 | Leisure Stone Table | Situated within a sylvan clearing, the centerpiece is a scenic vignette composed of a stone table and chairs, surrounded by a selection of broad-leaved trees. |
| S6 | Bamboo Forest | Nestled amidst the canopy of the boardwalk, the view is partially secluded by bamboo groves to the left and right, with close proximity to the ground. |
| S7 | Broad-Leaved Forest | Ensconced within the canopy of the boardwalk, the vista is partially secluded by broad-leaved trees on either side. |
| S8 | Canopy Walkway | Perched above the forest canopy, the walkway is flanked on one side by a 20 m slope adorned with lush vegetation. |

**Table 3.** Overview of Fuzhou National Forest Park plot.

| Plot Number | Plot Name | Plot Introduction |
|---|---|---|
| F1 | Entrance Square | Situated on the eastern edge of the entrance landscape zone, the main entrance plaza spans approximately 1.9 ha, featuring an asphalt surface adorned with tree pits. |
| F2 | Shade-Grown Botanical Garden | Nestled beneath a nutmeg grove on the northern side of the park's eastern grand entrance, a gently sloping, fertile woodland has been selected for the creation of a diverse tapestry of flora. Over 100 species of high-value plants have been carefully arranged. |

**Table 3.** *Cont.*

| Plot Number | Plot Name | Plot Introduction |
|---|---|---|
| F3 | Bamboo Grove | Positioned on an open expanse amidst a verdant tapestry of trees and bamboo, the site offers panoramic views and excellent ventilation. The ground cover is a harmonious blend of paved and grassy areas, creating a visually appealing and inviting space. |
| F4 | Bamboo Grove | The garden is home to an extensive collection of approximately 215 bamboo species. The sample plot is strategically situated along a winding path that meanders through a tranquil bamboo grove. |
| F5 | Log Platform | Perched beside the tranquil waters of August First Reservoir, a wooden platform invites visitors to immerse themselves in the picturesque surroundings. Flanked by a discreet security post and a charming kiosk, the platform centers upon a magnificent banyan tree. The reservoir's serene expanse and the captivating vista beyond create a captivating panorama. |
| F6 | Riverside Walkway | Nestled alongside the picturesque August First Reservoir, the Waterfront Promenade offers a tranquil respite. Towering Alexander palms grace both sides of the walkway, their graceful fronds swaying gently in the breeze. Beneath their verdant canopy, vibrant bougainvillea and crimson Fraser's photinia add splashes of color, while a verdant expanse of lawn carpets the opposite side. |
| F7 | Millennial Banyan Tree | The Millennial Banyan, a stately Ficus concinna Miq., stands as an iconic symbol of Fuzhou National Forest Park. Its ancient trunk soars majestically, its dense canopy casting a dappled shade upon the meticulously manicured understory. The tree's distinctive silhouette, with its elevated and uniform branches, has become synonymous with the park's enchanting beauty. |
| F8 | Pavilion in the Center of the Lake | To the north lies the Hydrophilic Arboretum, a verdant sanctuary for moisture-loving trees. To the south, the Millennial Banyan District unfolds its ancient grandeur. The western horizon is graced by the serene waters of August First Reservoir, while the east offers a glimpse into the Banyan Garden Scenic Area. Within the lake's crystal depths, hundreds of vibrant red and gold koi dance gracefully, adding a touch of enchantment to the landscape. |
| F9 | Hydrophilic Arboretum | Nestled at the southern edge of Banyan Garden, the Hydrophilic Arboretum is a verdant haven dedicated to moisture-loving trees. Scattered throughout the arboretum are three sets of stone tables and chairs, inviting visitors to pause and immerse themselves in the serene atmosphere. |

**Table 4.** Overview of Xihu Park plot.

| Plot Number | Plot Name | Plot Introduction |
|---|---|---|
| X1 | Gateway Bridge | At the heart of the Bonsai Garden, where the terrain levels and opens up, lies a petite plaza flanked by the visitor service center. |
| X2 | Bonsai Garden Entryway | Encircling the garden, a tapestry of verdant lawns and meticulously manicured bonsai shrubs unfolds, creating a serene and harmonious setting. A carefully crafted rockery, with its rugged peaks and cascading waterfalls, adds a touch of drama to the landscape, inviting visitors to contemplate the beauty of nature in miniature. |
| X3 | Bonsai Garden | Flanked by banyan trees, the stone-paved path is the garden's main thoroughfare, thronged by passersby. |
| X4 | Woodland Trail | A wooden footbridge spans the water, offering an unobstructed vista of the surrounding expanse. |
| X5 | Timbered Floating Bridge | By the water's edge, an observation deck flanked by two banyan trees extends over the water, providing expansive views on three sides, while a stone wall forms the backdrop on the fourth. |

**Table 4.** *Cont.*

| Plot Number | Plot Name | Plot Introduction |
|---|---|---|
| X6 | Waterfront Terrace | A recreational area is dominated by broadleaf and bamboo groves, with three sets of stone tables and chairs beneath the trees for visitors to rest upon. The ground is paved with a durable cement–pebble composite. |
| X7 | Broadleaf and Bamboo Forest Intermix | At the entrance to the flat and expansive Bonsai Garden, a small plaza is surrounded by the visitor service center. |

### *2.3. Overall Experimental Design*

This study aims to investigate the impact of the audio–visual environment of urban forests in Fuzhou on the physiological and psychological perception of the public in order to reveal the sensory experience of green spaces in the urban environment and their mechanisms of action. To this end, we selected three urban forests in Fuzhou, with a total of 24 representative sample points for study. By quantitatively measuring audio–visual landscape elements and combining this with real-time monitoring of the public's physiological indicators and questionnaire survey data collection, this study comprehensively evaluates the effects of urban forests on people's sensory experiences.

### *2.4. Audiovisual Environment Measurements*

#### 2.4.1. Visual Environment

Evaluating landscape quality is a multidimensional process involving multiple constituent indicators. In the field of research on the evaluation of landscape quality based on visual landscape elements, scholars propose four categories of key elements [10]: landscape spatial scale elements [11], physical landscape elements [12], color elements [13], and comprehensive elements [14]. Furthermore, drawing on research related to mountain parks [15], this study further identifies vegetation elements, water body elements, spatial elements, and construction elements as the main factors affecting the landscape quality of mountain forests. A comprehensive analysis of these elements helps to deeply understand the characteristics of the landscape and their impact on the visitor experience. A detailed classification and description of the elements are shown in Table 5.

**Table 5.** Overview of landscape elements.

| | Landscape Elements | Number | Scoring Criteria and Weightings |
|---|---|---|---|
| Plant elements | Plant proportion | Z1 | The proportion of the plant in the panoramic scene |
| | Plant color | Z2 | 1 point for no apparent chromatic aberration, 2 points for green hues of varying brightness, 3 points for the presence of flowers or colored foliage |
| | Plant layers | Z3 | 1 point for the absence of layers, 2 points for a single layer of vegetation, 3 points for a double layer of vegetation, 4 points for the presence of trees, shrubs, and grass |
| Water elements | Water proportion | S1 | The proportion of the water body in the panoramic scene |
| | Water presence | S2 | 1 point for presence, 0 points for absence |

**Table 5.** *Cont.*

| | Landscape Elements | Number | Scoring Criteria and Weightings |
|---|---|---|---|
| Spatial elements | Skyward proportion | K1 | The proportion of sky coverage within the panoramic scene |
| | Enclosure | K2 | Sum of tree, shrub, architectural structure, and fence coverage proportions within the panoramic scene |
| | Ground proportion | K3 | The proportion of the ground in the panoramic scene |
| Architectural elements | Pavement presence | J1 | 1 point for presence, 0 points for absence |
| | Scene complexity | J2 | 1 point for negligible presence of weeds or fallen leaves on paved surfaces (roads, plazas, etc.), 2 points for moderate presence, 3 points for substantial presence and untidiness |
| | Structure proportion | J3 | The proportion of buildings and structures (street lights, trash cans, etc.) in the panoramic scene |

Landscape feature extraction is foundational work in landscape research, involving various techniques and methods. This study adopts the following two main methods for landscape feature extraction. The first is image segmentation. Image segmentation is a fundamental technique in the field of computer vision and is of great significance for improving computers' ability to understand images. As shown in Figure 4, this study performs image segmentation processing on panoramic images of selected sample sites to extract landscape features.

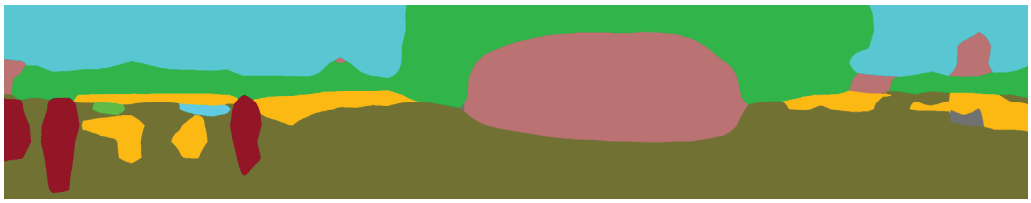


**Figure 4.** Scene image semantic segmentation graph.

The second is the ColorImpact color extraction method. This study uses ColorImpact 4.0.3 software to extract colors from the collected panoramic images to analyze the color characteristics of the landscape.

In this study, we collected panoramic images of 24 sample sites in three major urban forests in Fuzhou. Based on relevant research results in the field of mountain forest research, we identified four key factors that affect the landscape quality of mountain forests: vegetation, water bodies, space, and construction.

#### 2.4.2. Acoustic Environment

In this study, we conducted sound environment monitoring of three urban forests in Fuzhou, using high-precision sensors and high-fidelity recorders provided by Weihai Gemho Digital Mining Technology Co., Ltd, Weihai, China, to record volume and real-time sound at the sample sites. The monitoring period was from October to December 2020. Each experiment was conducted from 7:00 a.m. to 7:00 p.m., ensuring comprehensive coverage of the daytime sound environment. The monitoring equipment was placed at a height of 1.5 m above the ground, and data were collected every 2 h, with the average of three readings taken as the final record.

### 2.5. Measurement of Physiological Data from the Public

When exploring physiological and psychological indicators, skin electricity, heart rate, and respiratory rate are important physiological indicators for assessing the level of emotional calmness of an individual. Although these indicators can reflect the level of physiological arousal, they often cannot accurately distinguish between specific categories of emotions. For example, the literature [16] points out that these indicators mainly reflect the physiological activation state and cannot directly reveal the category of emotions.

However, from a general physiological response perspective, skin electrical activity shows an upward trend when an individual is tense, as described in the literature [17]. Conversely, in an individual's relaxed state, the heart rate will show a downward trend. Heart rate, the number of pulse beats per minute, is a key indicator for assessing the health of the cardiovascular system [18]. Changes in heart rate can reflect an individual's stress level and physiological arousal state. Under calm conditions, the normal heart rate range is 60–100 beats/min. When an individual experiences emotional tension or increased stress, the heart rate rises accordingly.

The low frequency (LF) component in heart rate variability is usually associated with sympathetic nervous system activity, while the high frequency (HF) component is closely related to parasympathetic nervous system activity [19]. The LF/HF ratio, the ratio of the low-frequency to high-frequency components of the heart rate, can reflect the dynamic changes in sympathetic and parasympathetic nerve activity [20]. Changes in the LF/HF ratio can effectively indicate an individual's psychological state, such as changes in tension, relaxation, or comfort.

The skin galvanic response (EDA) signal changes significantly with changes in emotion [21,22] and is often used to study subjects' responses to specific emotionally arousing environments or stimuli [23]. When faced with environmental stress, the skin conductance value exhibits sensitive changes, becoming an effective indicator reflecting emotional changes.

Therefore, this experiment will monitor the physiological indicators of the participants, including skin electricity, heart rate, and heart rate variability. To reduce external interference, the participants will watch the surrounding landscape in a fixed position so that their physiological and psychological responses can be captured more accurately.

### 2.6. Questionnaire Survey

This study aims to evaluate the impact of landscape perception on mental health and selects mental vigor, stress relief, emotional calmness, and attention restoration as evaluation indicators of mental health [24].

The questionnaire survey is divided into three main parts. The first part focuses on demographic characteristics, including personal background information, such as gender, age, stress level, professional background, and frequency of visits to urban forests. The second part focuses on the frequency and intensity of perception of various sounds in the forests, using the research method of Liu Jiang [25] to evaluate 17 typical sound sources. The evaluation criteria include perception frequency (1 point for never perceived, 2 points for occasionally perceived, and 3 points for often perceived) and perception intensity (1 point for quiet, 2 points for general, and 3 points for very strong). By multiplying the frequency and intensity scores, the dominance score of each sound is obtained, and it is reclassified into a 5-level scale: 1 for very low (1~2 points), 2 for low (3 points), 3 for general (4~5 points), 4 for high (6~7 points), and 5 for very high (8~9 points). Since bicycle sounds and frog calls were not recorded in the actual survey, this study actually evaluated 15 sounds. The specific evaluation results are shown in Table 6.

The third part involves the evaluation of visitor psychological indicators, as shown in Table 7, referring to the research of many scholars [26,27], using a 7-point Likert scale to set questionnaire questions and using 7 points as the full score for quantitative evaluation. Through such a structured questionnaire design, this study aims to explore the specific impact of landscape perception on individual mental health and provide a scientific basis for future urban planning and environmental design.

**Table 6.** Typical sound source composition in the case forests.

| Sound Type | Classification | Instruction |
|---|---|---|
| Artificial sound | The sound of human activity | Conversation, children's laughter, footsteps |
| | Mechanical sound | Traffic, aircraft, construction, bicycle bell, lawn mower, sweeping, public announcements, music |
| Natural sound | Geophysical sound | Wind, wind blowing the leaves, water |
| | Biological sound | Bird call, frog call, insect call |

**Table 7.** Meaning of Psychological Perception Questionnaire.

| Measures of Psychological Perception | Basic Meaning |
|---|---|
| Spiritual vitality | The state of an individual's mental vitality experienced within their environment |
| Stress relief | An individual can effectively release stress within their environment |
| Emotional arousal | After experiencing their environment, an individual alleviates and releases negative emotions, such as anxiety, leading to a more moderate emotional state |
| Attention recovery | Natural environments are conducive to the recovery of human attention and have the effects of promoting positive emotions, alleviating stress, and relieving mental fatigue; natural space environments that meet the four basic characteristics of being away, richness, fascination, and compatibility possess the function of attention restoration |

### *2.7. Subjects*

When conducting research related to visual stimuli, ensuring the representativeness of the participants and the adequacy of the sample size is crucial for improving the scientific nature and generalizability of the research results. Researchers such as Kaplan [28] have pointed out that the college student population can provide highly scientific and representative data in such experiments. Therefore, this study used G*Power 3.1 software to conduct a rigorous power analysis to determine the appropriate sample size to ensure that the experiment had sufficient statistical power.

Through the calculations of G*Power software, we determined the minimum sample size required under the given effect size, $\alpha$ level (usually 0.05, indicating the significance level), and statistical power (usually 0.80 or higher). Based on these calculations, we selected 77 undergraduate students from different majors as the experimental subjects. This sample size not only meets the requirements of statistical power but can also effectively represent a wider young adult population.

The age of all the participants was under 30 years old, with an average age of 23.4 years old. The selection of this age range helps to ensure that the participant performance on cognitive and perceptual tasks is consistent and reduces the potential impact of age-related cognitive differences on the experimental results. During the screening process, we excluded individuals with a history of major physical or mental trauma, major surgery, or chronic diseases, such as heart disease and hypertension, to ensure that their health status would not bias the experimental results.

### *2.8. Experimental Procedure*

This study was conducted from October to December 2020 in three forests in Fuzhou—Jinniushan Sports Park, Fuzhou National Forest Park, and Xihu Park in Fuzhou—for a period of 7 to 14 days. The experimental time was scheduled from 7:00 a.m. to 7:00 p.m. each day to cover different time periods during the day. Each day, we invited 3 to 5 participants to participate in the experiment, and each participant's observation time in each forest was controlled between 1.5 and 3 h.

Before the experiment started, the project leader gave detailed face-to-face instructions to the 77 participants, introducing the basic concepts of visual and auditory landscapes, the purpose and significance of the experiment, and explaining, in detail, how to fill out the questionnaire, including the meaning of each question and answer option. The

research team then led the participants to 24 selected sample sites for physiological index measurement. In addition, after reaching each site, the subjects had to rest for 5 to 10 min to ease the physical and psychological indicators.

As Figure 5 shows, in the specific physiological index detection experiment, the participants were equipped with calibrated physiological monitoring equipment, and while observing the sample site landscape and listening to the ambient sound for 3 min, they were required to refrain from talking, eating, or drinking to reduce man-made interference during the experiment. The researchers were responsible for recording the participants' physiological index data in real time. After the perception session of each sample site, the participants filled out the relevant questionnaire survey.

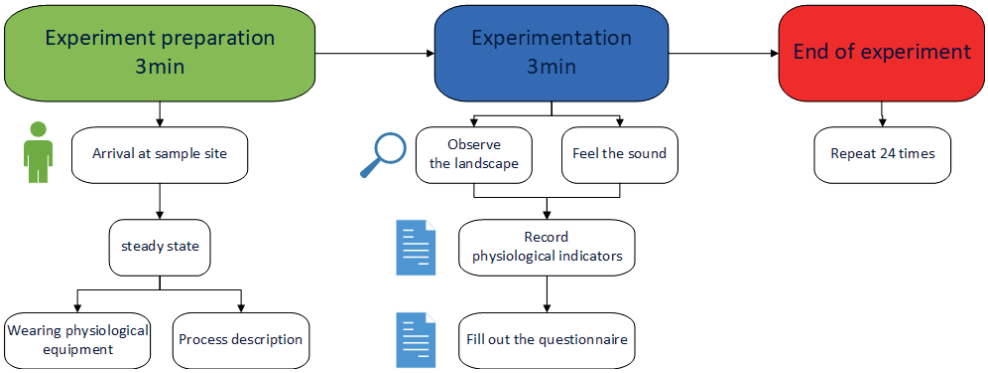



**Figure 5.** Procedure.

### *2.9. Analytical Methods*

To explore the relationship between the audiovisual environmental elements in the scene and the physiological and psychological perception responses of the subjects to the studied scene and to identify their potential relationships, stepwise regression analysis was performed on the data to investigate whether there is a correlation between these elements and the strength and direction of the correlation to better understand the impact of the combined audiovisual effect on the public response.

## 3. Results

### *3.1. Base Environmental Conditions*

In this study, we used advanced programming language technologies, such as Java and Python, to precisely segment the panoramic images taken of the selected sample sites to identify and extract different ecological patches. Through this image-processing method, we were able to analyze the landscape structure in detail, leading to a deeper understanding of the complexity of the ecosystem.

Furthermore, we carried out meticulous color extraction work on the generated patches. To ensure the accuracy and consistency of color recognition, we used professional ColorImpact 4.0.3 software to systematically analyze and recognize the extracted colors. Through the software's color scheme design function, we obtained detailed data on the color composition and distribution of the sample site landscape, which are organized and presented in Table 8. In addition, we conducted a detailed investigation and analysis of the soundscape dominance in the three forests in Fuzhou. The collected data reveal the uniqueness of the sound environment in each forest. Specifically, the soundscape indicators of the mountain forest are generally lower than the average level, indicating that the environment in this area is relatively quiet, with less noise generated by human activities.

In contrast, the data from the mountain–water forest show a higher dominance of conversation, children's play, and footsteps, which indicates higher foot traffic and frequent social interactions within the forest. The soundscape of the waterfront forest is obviously dominated by natural elements, especially the sound of water and birdsong, creating a stronger natural atmosphere. These results are clearly shown in Table 9.

**Table 8.** Quantitative analysis of plant landscape elements in different urban forests.

| Type | Plant Proportion | Plant Color | Plant Layers | Structure Proportion | Pavement Presence | Scene Complexity | Skyward Proportion | Ground Proportion | Enclosure | Water Proportion | Water Presence |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mountain | 57.78 | 2 | 2.62 | 16.12 | 0.50 | 2.50 | 8.07 | 18.02 | 73.90 | 0 | 0 |
| Mountain–water | 51.44 | 1.56 | 2.44 | 6.21 | 0.89 | 2.89 | 6.44 | 30.14 | 57.65 | 4.48 | 0.44 |
| Waterfront | 46.26 | 2.14 | 3.14 | 8.89 | 0.87 | 2.43 | 9.32 | 28.00 | 55.15 | 6.42 | 0.57 |

**Table 9.** Soundscape dominance analysis of forests.

| Type | Conversation | Children's Laughter | Foot-Steps | Traffic | Aircraft | Construction | Lawn Mower | Sweeping | Public Announcements | Music | Wind | Wind Blowing the Leaves | Water | Bird Call | Insect Call |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mountain | 2.26 | 1.96 | 2.08 | 1.58 | 1.20 | 1.39 | 1.18 | 1.30 | 1.83 | 1.58 | 1.92 | 1.95 | 1.23 | 2.24 | 1.94 |
| Mountain–water | 5.69 | 5.08 | 4.72 | 2.43 | 1.22 | 1.89 | 1.78 | 2.11 | 3.50 | 4.39 | 4.67 | 5.04 | 4.06 | 5.29 | 3.46 |
| Waterfront | 4.35 | 2.82 | 3.85 | 2.51 | 1.46 | 2.83 | 1.96 | 1.83 | 2.61 | 3.10 | 3.43 | 4.01 | 4.28 | 4.17 | 2.93 |

### 3.2. The Combined Effect of Visual–Acoustic Stimuli on the Physiological Indices of the Public

#### 3.2.1. Effects on HR

- As shown in Figure 6, in the study of HR across three forests in Fuzhou, the mountain–water forest exhibited the highest average HR (81.82 beats per minute), followed by the waterfront forest (83.34 beats per minute), with the mountain forest recording the lowest average (69.55 beats per minute), all within the normal physiological range. Further analysis of HR variability reveals significant differences among the forests, with the mountain–water forest showing the greatest variation, followed by the waterfront forest and then the mountain forest. Statistical analysis, including analysis of variance (ANOVA) and least significant difference (LSD) post hoc tests, confirmed these differences to be highly significant. These findings suggest that the distinct landscape features and spatial experiences of the forests have varying impacts on the psychological and physiological well-being of visitors. The environments of the mountain and waterfront forests appear to be more effective in alleviating visitor stress, leading to more stable heartbeats and a trend toward decreased HR;

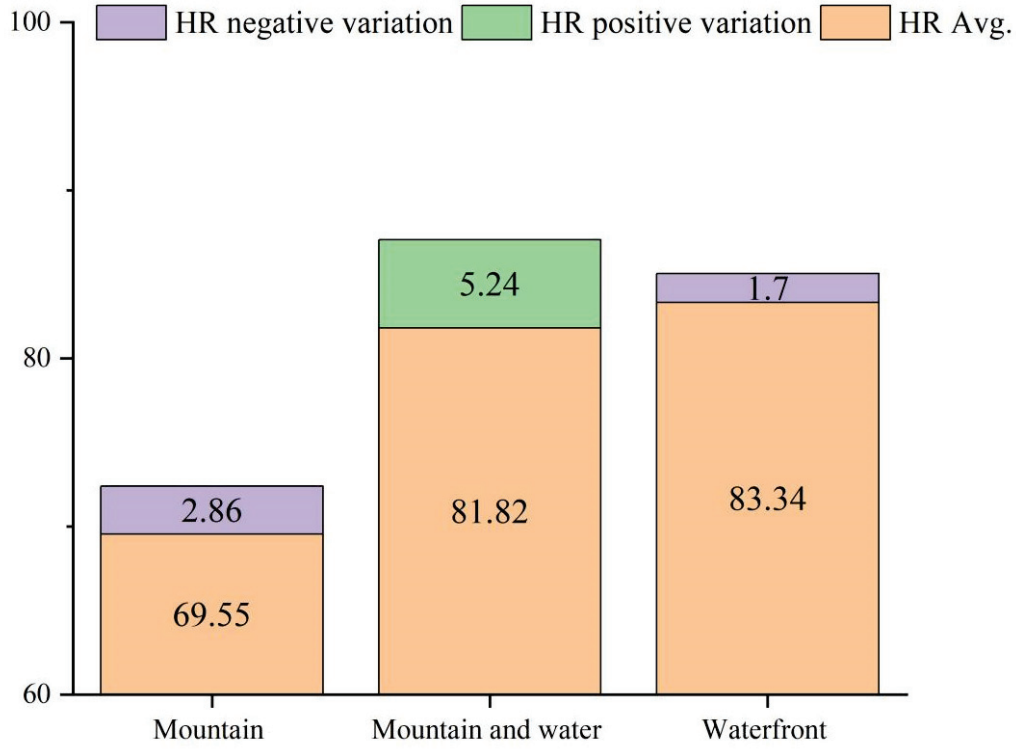



**Figure 6.** Average and change values of HR in Fuzhou urban forests.

- According to the research results shown in Figure 7, among the eight sample sites in the mountain forest, we observed positive changes in the subjects' HR values in the S3 and S4 sample sites, while negative changes occurred in the S1, S2, S5, S6, S7, and S8 sample sites. To further explore the impact of different sample sites on HR change values, we conducted an LSD multiple comparison test;
- The test results show that there were significant differences in HR change values between S3 and S8 ($p = 0.046$), S4 and S8 ($p = 0.023$), and S4 and S7 ($p = 0.041$). These findings indicate that most sample sites in the mountain forest can effectively reduce the stress levels of the subjects, leading to a decrease in HR values. It is particularly noteworthy that S8, located in an open field of vision, has a significant effect on reducing the heart rate of the public;

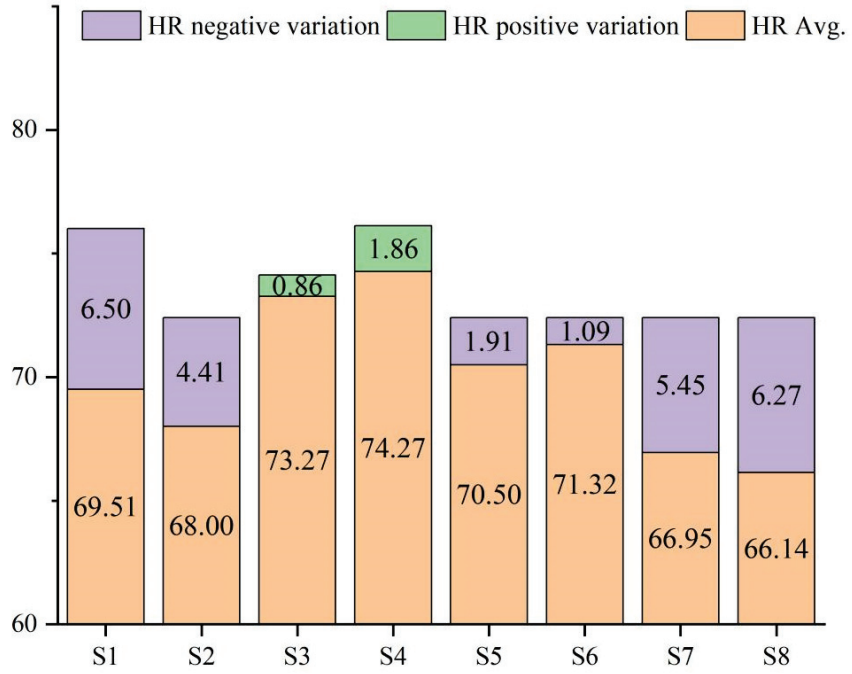



**Figure 7.** Average and change value of HR in mountain forest.

- According to the data presented in Figure 8, among the nine sample sites in the mountain–water forest, the HR of the participants generally showed a positive change; that is, the heart rate increased, and these changes did not show significant differences statistically. In terms of the change trend, the HR change value of F8 was the highest, followed by F1, while the HR change value of F5 was the smallest;
- This result indicates that the different sample sites in the mountain–water forest generally increased the stress levels of the participants, leading to a general increase in HR. In particular, F8 seemed to have the greatest stress impact on the participants, as evidenced by a significant increase in heart rate. In contrast, F5 had the least stress impact on the participants, with a relatively small increase in HR;

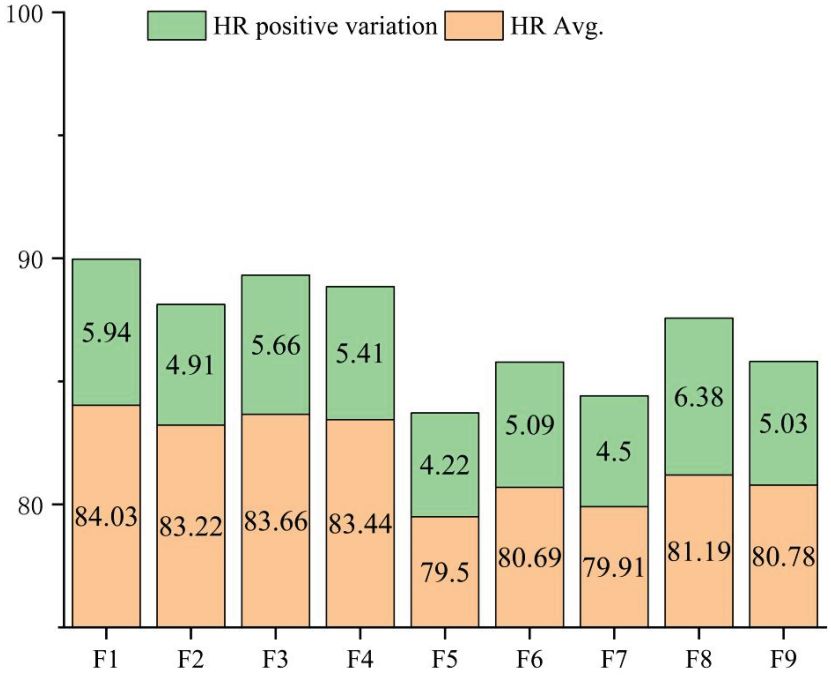



**Figure 8.** Average and variation of HR in mountain–water forest.

- According to the research results shown in Figure 9, among the seven sample sites in the waterfront forest, the HR changes of the participants showed varying degrees of negative changes; that is, the heart rate generally decreased. Specifically, the HR change value of X6 was the largest, followed by X2, then X4, X1, X5, X3, and X7. Despite this, these changes did not reach a significant level statistically;
- In the waterfront forest, all sample sites showed a stress-relieving effect on the participants, as evidenced by the decrease in HR. This phenomenon indicates that the landscape design of the waterfront forest has, to a certain extent, promoted relaxation and stress reduction among visitors. However, since the differences in HR change values between the sample sites were not significant, this may imply that the stress-relieving effects of different areas in the forest are relatively uniform or that further research is needed to explore the potential differences and the specific effects of specific landscape features on psychological relaxation. In summary, the sample sites in the waterfront forest generally had a mitigating effect on the psychological stress of the participants.

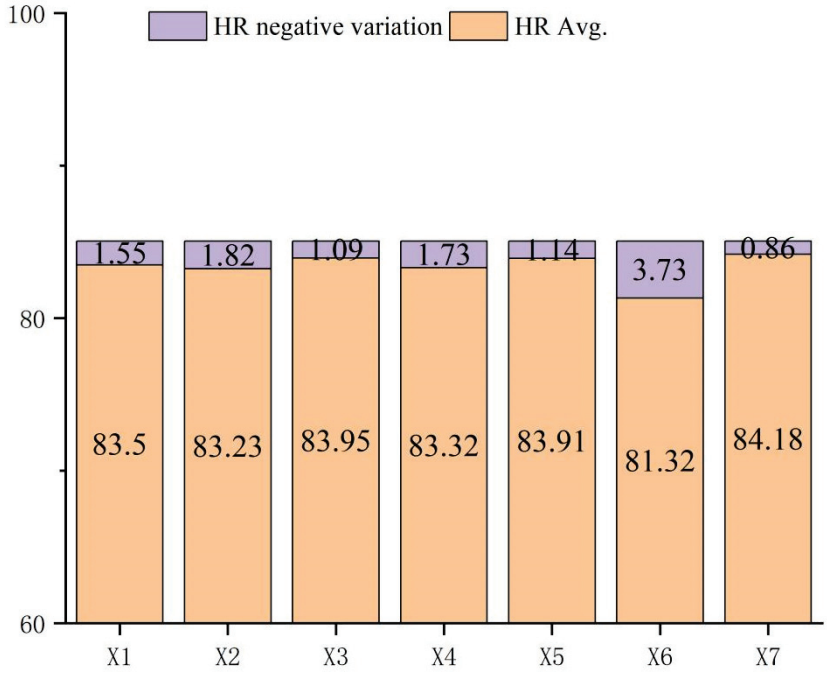



**Figure 9.** Average and change value of HR in waterfront forest.

3.2.2. Effects on the Heart Rate LF/HF Balance

- According to the data presented in Figure 10, the low-frequency-to-high-frequency heart rate variability ratio (LF/HF) of the mountain–water forest was the highest on average, followed by the mountain forest, while the average LF/HF of the waterfront forest was the lowest. This indicator reflects the tension level of the subjects in the three different forests and its impact on the activity of the autonomic nervous system. The research results show that all three forests led to an increase in the LF/HF values of the subjects; that is, they increased the activation level of the sympathetic nervous system, reflecting an increase in the tension level of the subjects. However, there were differences in the degree of influence, with the waterfront forest having the highest level of tension, followed by the mountain forest, and the mountain–water forest having the least influence. In the mountain–water forest, the sympathetic nerve arousal level of the subjects was relatively low, and the change in LF/HF value was also the most limited;

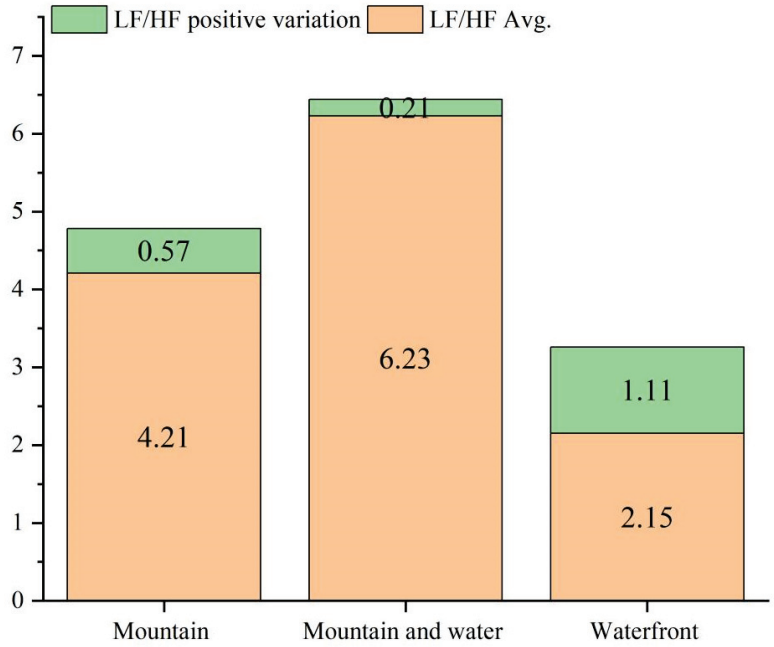



**Figure 10.** Average value and change value of heart rate balance ratio (LF/HF) in Fuzhou urban forests.

- According to the data analysis results in Figure 11, in multiple sample sites in the mountain forest, the heart rate balance ratio (LF/HF) of the participants showed varying degrees of positive and negative changes. Specifically, the LF/HF change value of S7 was the largest, followed by S1 and S8, followed by S5, S3, S4, and S6;
- By performing the LSD multiple comparison test, we found that there were significant differences in the LF/HF change values between S1 and S6, S3 and S7, S4 and S7, and S6 and S7. These results reveal the specific effects of different sample sites on the participants' autonomic nervous system activity;
- In particular, S3, S4, and S6 seem to be able to effectively reduce the anxiety level of the participants, as evidenced by enhanced parasympathetic nerve activity and decreased LF/HF values. However, in other sample sites, such as S1 and S7, the participants' anxiety and tension levels were relatively high, as reflected by an increase in LF/HF values;

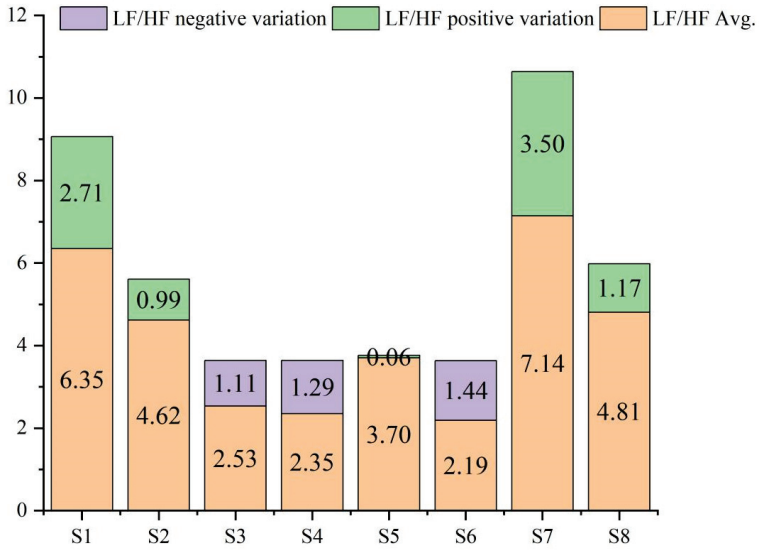



**Figure 11.** Average value and change value of heart rate balance ratio (LF/HF) in mountain forest.

- According to the data shown in Figure 12, the influence of different sample sites in the mountain–water forest on the heart rate balance ratio (LF/HF) of the participants showed positive and negative changes. Specifically, the LF/HF change values of F2, F5, and F6 were relatively large, while the LF/HF change values smaller for F3, F7, F8, F1, F4, and F9;
- The research results reveal that F1, F4, and F9 have a significant relaxation effect on the participants, resulting in a decrease in LF/HF values, among which the relaxation effect in F9 is the most significant. In contrast, in the other six sample sites, the participants generally experienced different degrees of emotional tension, which led to increased sympathetic nerve activity and a corresponding increase in LF/HF values;

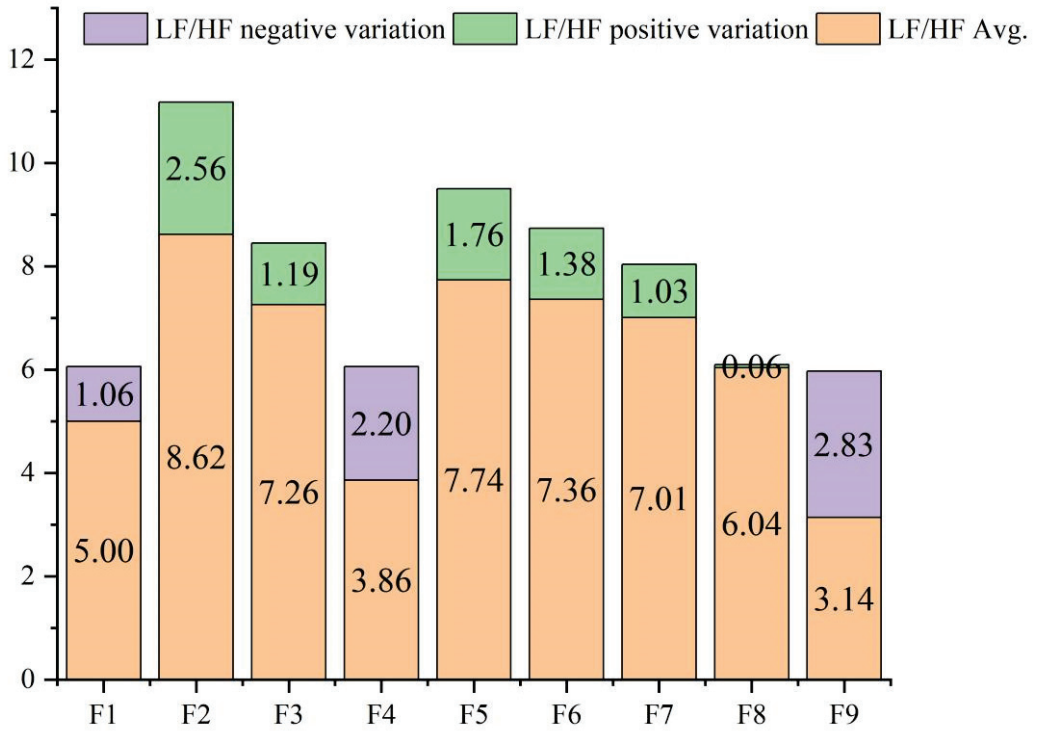



**Figure 12.** Average value and change value of heart rate balance ratio (LF/HF) in mountain–water forest.

- According to the data presented in Figure 13, the seven sample sites in the waterfront forest generally had a negative impact on the heart rate balance ratio (LF/HF) of the participants, indicating that the parasympathetic nervous system activity was relatively enhanced, and the participants' psychological state was effective. It has been soothed and relaxed. Among these sample sites, X6 has the most significant effect on reducing LF/HF values, while X5 has a relatively weak relaxation effect, although all sample sites show a tendency to promote relaxation;
- In terms of specific change values, the LF/HF change value of X6 is the largest, followed by X3 and X4, followed by X2, X1, and X7. These results reveal the specific effects of different sample sites in the waterfront forest on the participants' autonomic nervous system activity and point out the importance of landscape features that should be considered in park design for promoting visitor relaxation. In summary, the sample sites in the waterfront forest generally help to reduce the tension of the participants, among which specific areas, such as the waterfront platform, are particularly effective in promoting psychological relaxation.

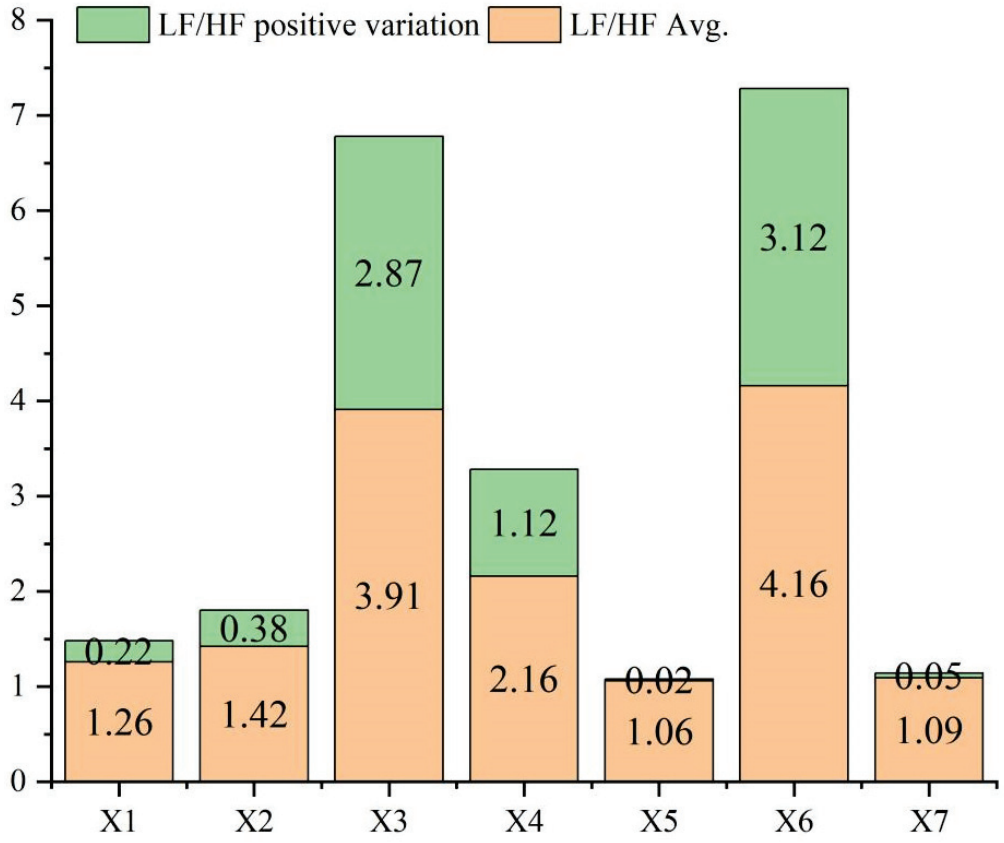



**Figure 13.** Average value and change value of heart rate balance ratio (LF/HF) in waterfront forest.

3.2.3. Effects on EDA

- According to the data analysis results in Figure 14, the EDA change values of the participants in the three forests showed different trends, with the change value in the mountain forest being the largest, followed by the mountain–water forest, and the change value in the waterfront forest was the smallest. Through an ANOVA test, we found that there was no significant difference in EDA change values among the three forests ($F(2, 615) = 1.029$, $p = 0.358$);
- The research results reveal that in the mountain forest and the mountain–water forest, the participants' mood fluctuated more, leading to an increase in the average EDA value. In contrast, in the waterfront forest, the participants' psychological states were relatively more stable, and the average EDA value showed a downward trend. This difference may be related to the geographical location and usage frequency of the waterfront forest. As a comprehensive forest located in the city center, Xihu Park has high accessibility and daily usage frequency, so for regular visitors, there may be a lack of novel experience;
- It is worth noting that many participants said that this was their first visit to Jinniushan Sports Park and Fuzhou National Forest Park. The novel experience of these two forests may have a greater impact on the participants' emotions, leading to an increase in EDA conductance;

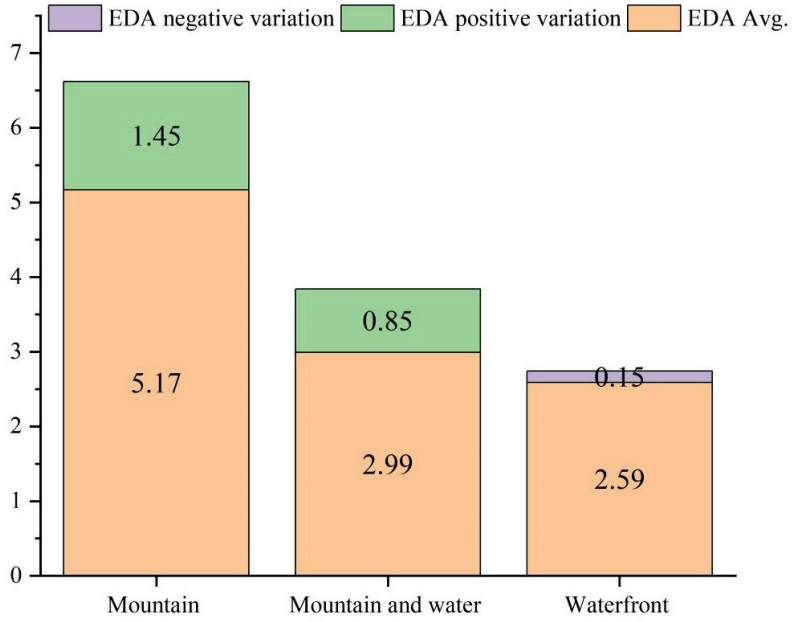



**Figure 14.** Average value of EDA in Fuzhou urban forests.

- According to the research results shown in Figure 15, among the eight sample sites in the mountain forest, the EDA of the participants generally showed positive changes, indicating an increase in emotional fluctuations. Specifically, the EDA change value of S7 was the highest, indicating that the area had the most significant impact on the participants' emotions. This was followed by S6, while the EDA change value of S1 was the smallest, indicating that its impact on emotional fluctuations was relatively weak;
- These findings indicate that different sample sites in the mountain forest differ in their ability to induce emotional fluctuations. S7 may have a stronger emotional arousal effect on the participants due to its specific environmental characteristics or atmosphere. In contrast, S1 and S5 were relatively calm, with less impact on the participants' emotional fluctuations;

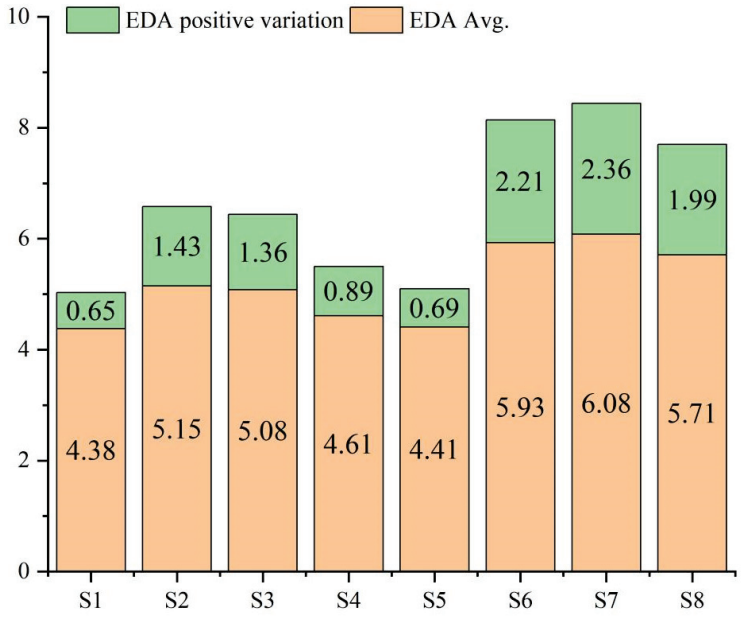



**Figure 15.** Average value and change value of EDA in mountain forest.

- According to the data shown in Figure 16, among the nine sample sites in the mountain–water forest, the participants' EDA all showed positive changes, indicating that emotional fluctuations increased. Among these sample sites, the EDA change value of F9 was the most significant, followed by F4, while the EDA change value of F5 was the smallest, indicating that its impact on emotional fluctuations was relatively weak;
- The research results reveal that different sample sites in the mountain–water forest have different effects on the participants' emotional fluctuations. F9 may have a more significant impact on the participants' emotions due to its unique environmental characteristics. In contrast, F1, F2, F3, F4, and F8 have a moderate and similar level of influence on the participants' emotions. F5 showed the least impact on emotional fluctuations, which may be related to the specific environmental design or atmosphere of the sample site;

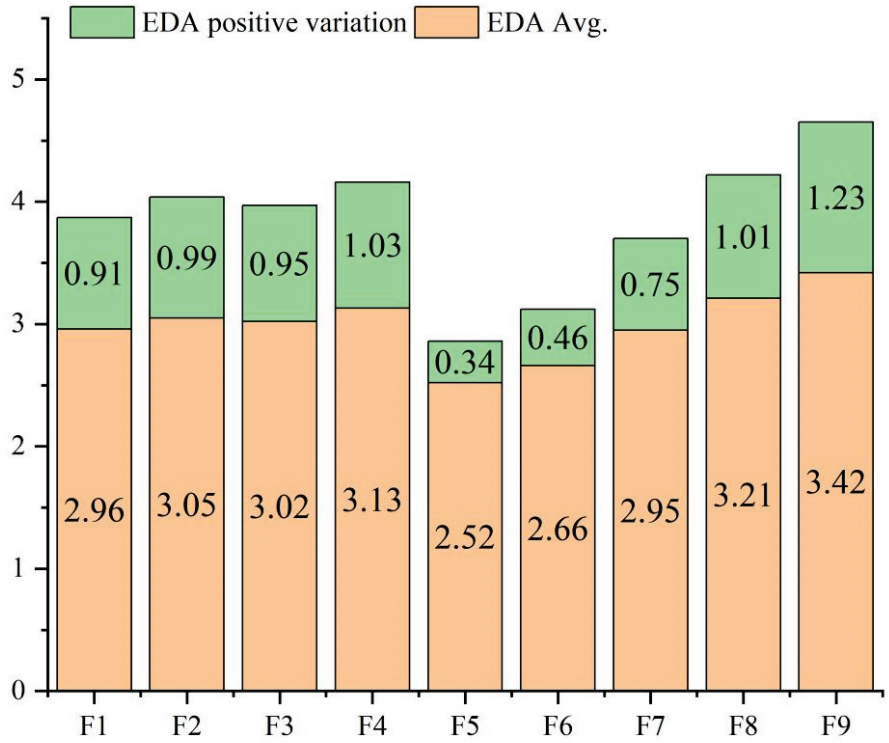



**Figure 16.** Average value and change value of EDA in mountain–water forest.

- According to the data shown in Figure 17, among the seven sample sites in the waterfront forest, the participants' EDA generally showed negative changes, indicating that emotional fluctuations were effectively relieved. Among these sample sites, the EDA negative change in X7 was the most significant, followed by X3, while the negative change in X4 was the smallest, indicating that its contribution to emotional relief was relatively weak;
- The research results show that different sample sites in the waterfront forest generally have the effect of mitigating the emotional fluctuations of the participants. In particular, X7 performed the best in reducing emotional fluctuations. X2, X3, X5, and X6 have similar effects on soothing emotions, with changes of about 0.15. In contrast, X4 has a relatively weak effect on soothing emotions.

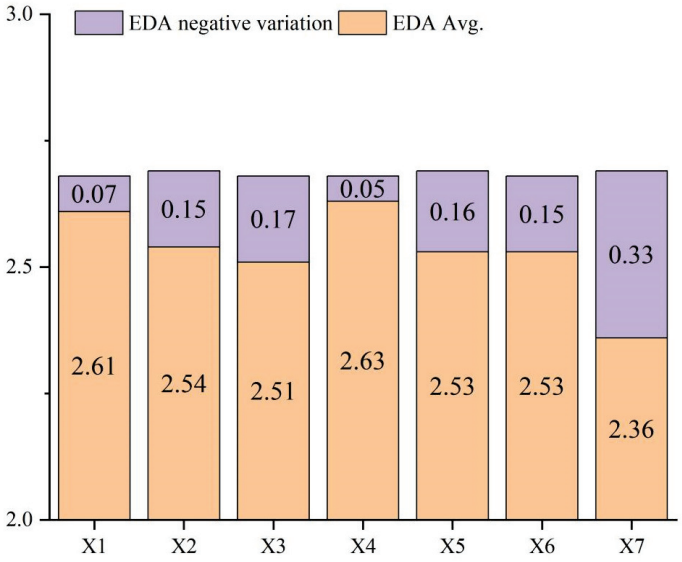



**Figure 17.** Average value and change value of EDA in waterfront forest.

### *3.3. The Combined Effect of Visual–Acoustic Stimuli on the Psychological Indices of the Public*

#### 3.3.1. Spiritual Vitality

- Figure 18 shows the results of a comparative analysis of the participants' mental energy levels in three different forest settings: a mountain forest, a mountain–water forest, and a waterfront forest. The analysis shows that the participants in the waterfront forest had the highest mental energy level, followed by the mountain–water forest, while the mental energy level of the mountain forest was relatively low. However, through statistical tests, it was found that the differences between the three were not statistically significant ($p$ = 0.193), indicating that the three forests were similar in their ability to improve the participants' mental energy;
- The waterfront forest scored the highest in terms of mental energy level, which may be attributed to its beautiful natural environment and rich cultural atmosphere, which may have had a positive psychological impact on the participants. In comparison, Jinniushan Sports Park featured a suspended walkway, which may have had a certain impact on the participants' sense of psychological security and, in turn, had a certain negative impact on their mental energy;

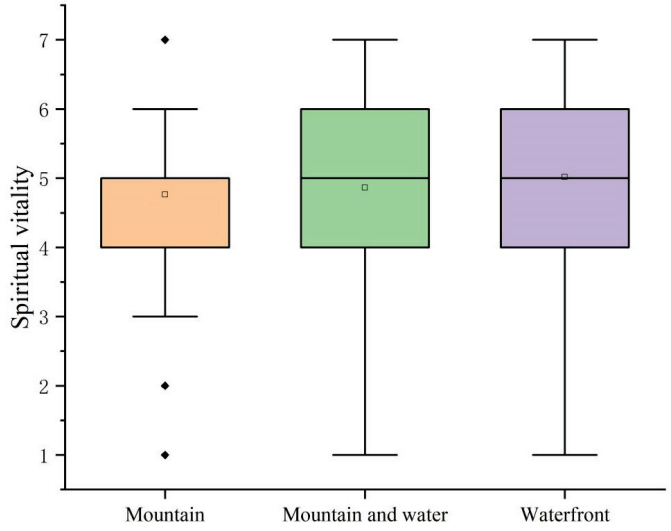



**Figure 18.** Comparative analysis of spiritual vitality in forests. Note: ◆ mild outlier.

- Figure 19 shows the mental energy of each sample site in the three forests. For the mountain forest, the mental energy score of S1 was relatively low, which may be related to the area's hard ground and urban characteristics. These factors may diminish the comfort of the natural environment, thereby adversely affecting people's mental energy. In contrast, S5 received the highest score, suggesting that its rich landscape types and clean site environment may be more conducive to improving the participants' mental energy;
- In the mountain–water forest, F7 received the highest mental energy score, which suggests that natural landscapes with historical and cultural value may have a significant positive effect on people's mental energy. At the same time, F1 received the lowest score, which may be related to disturbing factors, such as noisy crowds and traffic, which may have a negative impact on the participants' mental energy. Additionally, the higher scores of F9 and other forest recreation areas such as F2 and F4 indicate that a quiet natural environment and beautiful scenery have a positive effect on mental energy;
- In the waterfront forest, X3 received the highest score, which may reflect the importance of a well-designed landscape in enhancing mental energy. The relatively low scores of X1 and X6 may be related to their geographic location and surrounding environment, suggesting that these areas may need further improvement and optimization to enhance people's mental energy.

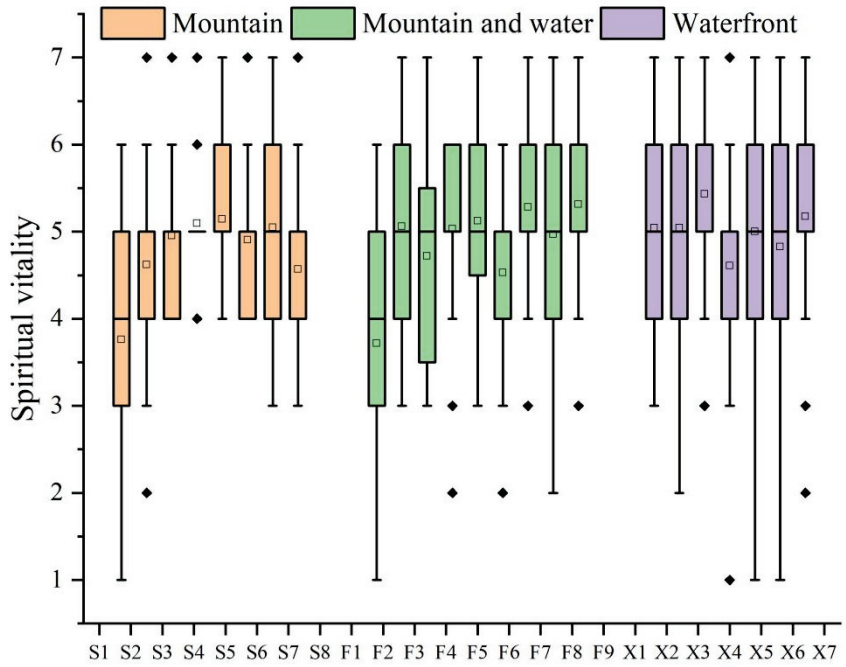



**Figure 19.** Comparative analysis of spiritual vitality in sample sites. Note: ◆ mild outlier.

3.3.2. Stress Relief

- Figure 20 provides the results of a comparative analysis of a mountain forest, mountain–water forest, and waterfront forest in terms of stress relief. The analysis shows that the waterfront forest has the highest score in terms of stress relief, followed by the mountain–water forest, while the mountain forest ranks third. However, through statistical tests ($p$ = 0.413), we found that the differences in stress relief effects among the three forests were not statistically significant, indicating that they all have certain effects in mitigating visitor stress. It is worth noting that the stress relief scores of the three forests are all close to 5 points, which indicates that these forests all play a positive role in providing a relaxing and de-stressing environment for visitors;

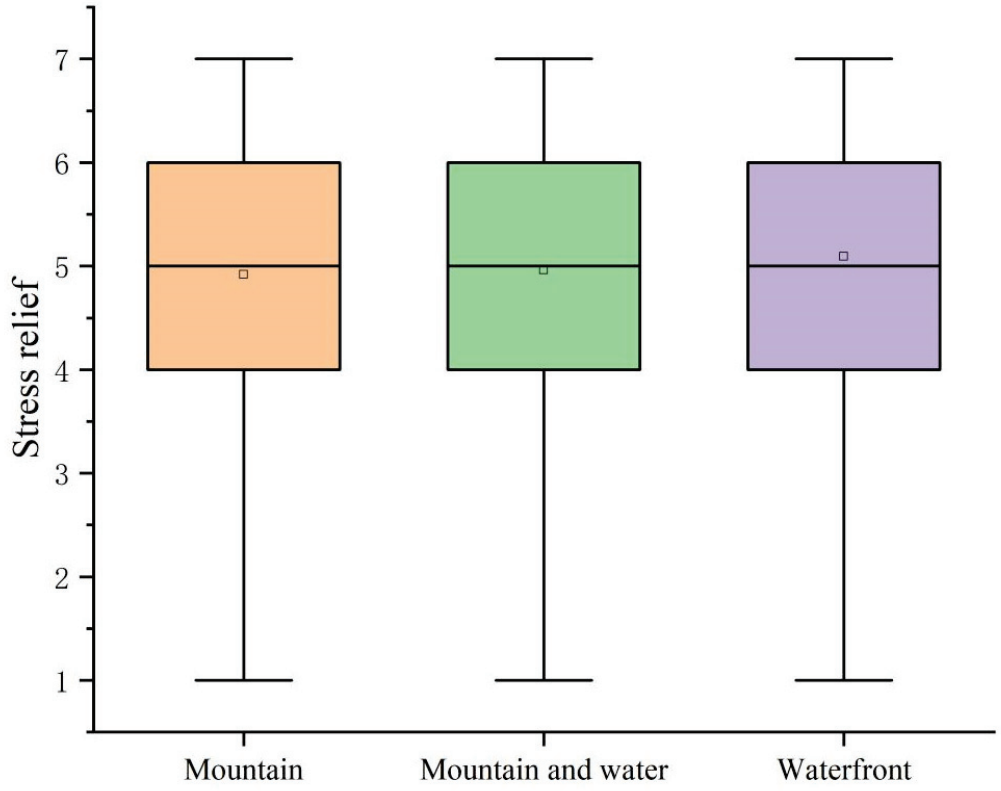



**Figure 20.** Comparative analysis of stress relief in forests.

- In the comparative analysis of the stress relief effects of sample sites in mountain, mountain–water, and waterfront forests, as shown in Figure 21, we observed significant differences between sites;
- For the mountain forest, S5 showed significant advantages in providing stress relief compared to other sites. This result may be attributed to the relatively natural and quiet environmental characteristics of S5, which helps promote psychological relaxation for visitors. In contrast, as a heavily trafficked entrance area, S1 had a relatively weak stress relief effect. The stress-relieving effects of other sites in the forest showed no significant differences, indicating that the forest may have met the relaxation needs of visitors in a relatively balanced manner in its overall design;
- In the mountain–water forest, F7 received the highest score for stress relief due to its unique natural landscape and historically significant ancient trees. This suggests that landscapes with ecological and cultural value may have a stronger appeal to visitors, thus enhancing their connection to and immersion in the natural environment. F1, also as an entrance area, may be negatively affected by traffic and noise, resulting in its poor stress relief effect. In contrast, forest plots, such as F9 and F4, despite providing a relatively quiet environment, did not show significant differences in stress relief effects;
- The analysis of the waterfront forest shows that X3 is slightly superior due to its exquisite landscape design, which may provide visitors with a visual feast and psychological relaxation. The stress relief effect of X7 is significantly better than that of plot X4, which may be related to the natural sounds and tranquil environment it provides, which together promote the psychological restoration of visitors. Although waterfront plots, such as X5 and X6, provide water-related landscapes, their stress-relieving effects did not show significant differences.

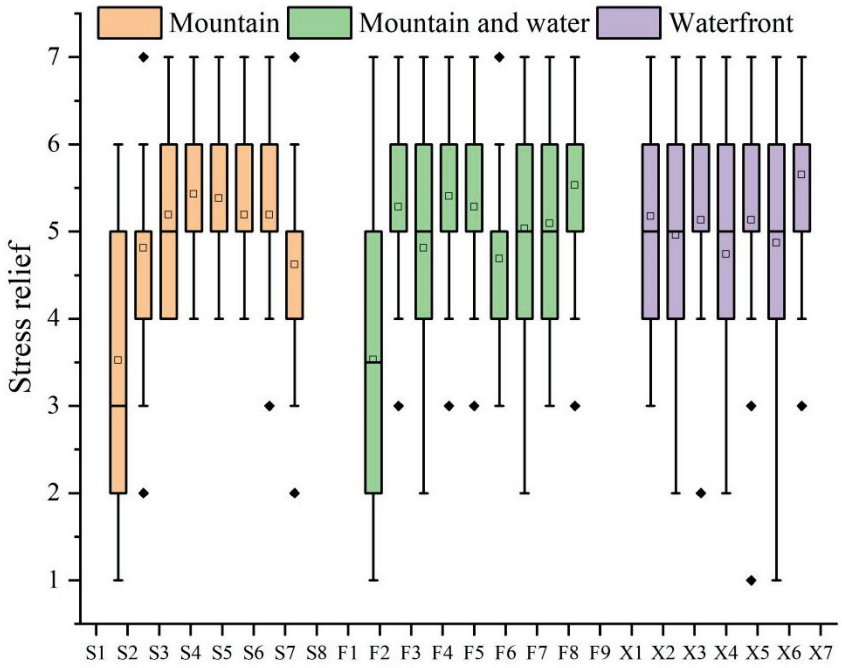



**Figure 21.** Comparative analysis of stress relief in sample sites. Note: ♦ mild outlier.

3.3.3. Emotional Arousal

- When comparing the emotional calming effects of mountain, mountain–water, and waterfront forests, we refer to the data in Figure 22. The analysis results show that the waterfront forest has the highest score in terms of emotional calming, followed by the mountain forest, and the mountain–water forest ranks third. However, through statistical tests ($p$ = 0.368), we found that there is no significant difference in the emotional calming effects of the three forests. It is worth noting that the emotional calming scores of the three forests are all close to 5 points, which indicates that these forests can effectively promote emotional stability and arousal to some extent.

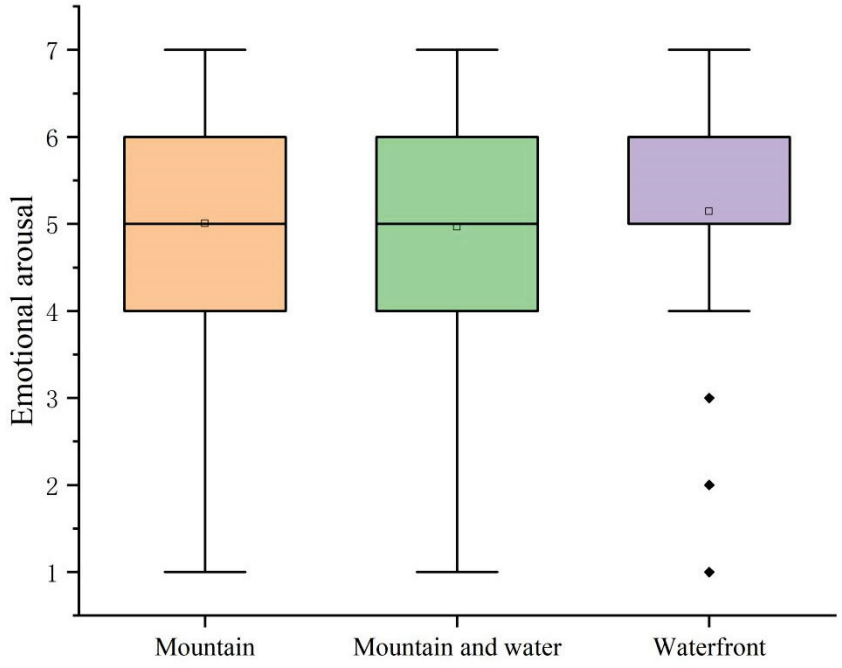



**Figure 22.** Comparative analysis of emotional arousal in forests. Note: ♦ mild outlier.

- As Figure 23 shows, among the sample sites in the mountain forest, S5 showed a better emotional calming effect compared to other sites, which may be related to the quiet environment it provides. In contrast, S1, being close to a major urban traffic road, may have a negative impact on emotional calming due to the noisy sound environment. In addition, there was no significant difference in the emotional calming effect between S4 and S3, while S6 was slightly better than S7, S2, and S8 in emotional calming, which may be related to the specific environmental characteristics of S6;
- The analysis of the sample sites in the mountain–water forest shows that the emotional calming effect of F7 is the most significant, while the emotional calming effect of F1 is relatively low due to the heavy traffic flow as an entrance area. F4 and F9 have similar effects in emotional calming and are both better than F2, but this difference is not statistically significant. Among the waterfront sample sites, the emotional calming effect of F5 is significantly better than F8 and F6, which may be related to the resting space and landscape quality provided by F5;
- Among the sample sites in the waterfront forest, X3 and X7 perform better in emotional calming, which may be due to their peaceful environment and beautiful natural scenery, which provide visitors with a space conducive to emotional recovery. In comparison, the emotional calming effect of X4 is relatively weak due to the large flow of people and the noisy environment. The waterfront plots X5, X1, and X6 are similar in emotional calming effects, with no significant difference, indicating that these plots may have common benefits in promoting emotional stability;
- Overall, the sample sites in the three forests have a certain effect in emotional calming, but the specific degree of effect may vary depending on the environmental characteristics of the site.

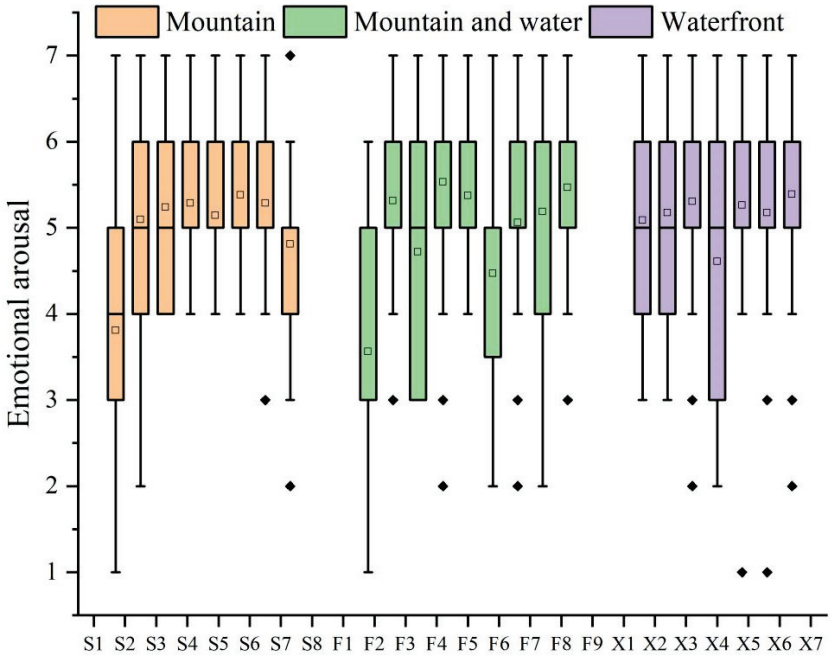



**Figure 23.** Comparative analysis of emotional arousal in sample sites. Note: ◆ mild outlier.

3.3.4. Attention Recovery

- In comparing the attention restoration effects of sample sites in mountain, mountain–water, and waterfront forests, we refer to the data in Figure 24. The analysis results show that the waterfront forest has the highest score in terms of attention restoration, followed by the mountain–water forest, and the mountain forest ranks third. Despite this, the differences in attention restoration effects among the three forests did not reach statistical significance ($p = 0.102$);

- It is worth noting that the attention restoration scores of the three forests are all concentrated around 5 points, which suggests that these forests can all promote the attention restoration of visitors to a certain extent. The waterfront forest received the highest score, which may be related to its beautiful natural landscape and rich cultural environment. The comprehensive and functional landscape planning of the waterfront forest may have had a certain positive impact on the attention restoration of visitors;

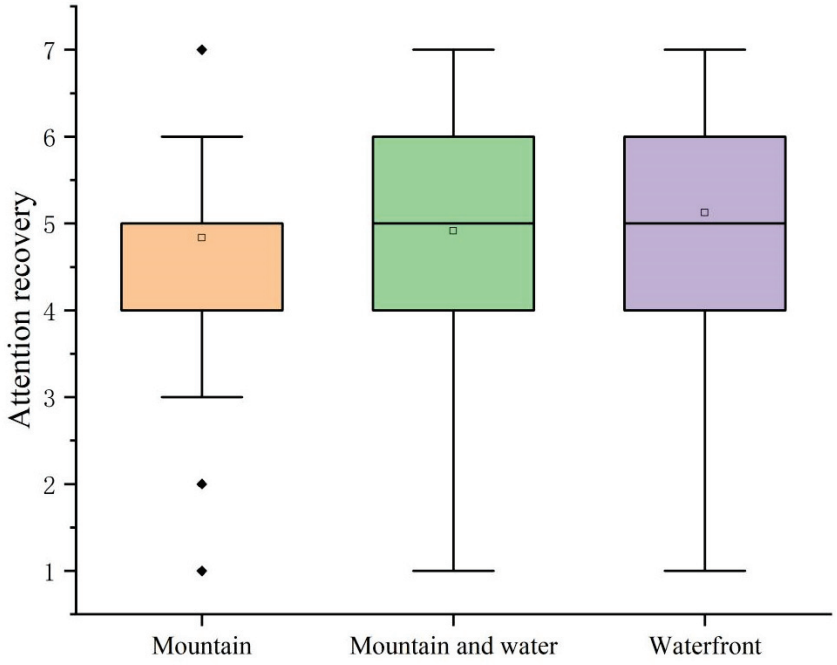



**Figure 24.** Comparative analysis of attention recovery in forests. Note: ◆ mild outlier.

- As Figure 25 shows, in the mountain forest, there were significant differences in the attention restoration effects among the sample sites, with some sites, such as S5, providing significantly better restoration effects than others. This may be related to the environmental characteristics of S5, such as its higher canopy cover and natural atmosphere, which may be more conducive to the attention restoration of visitors. In contrast, areas with more noise, such as S1, have a lower effect on attention restoration;
- The sample sites in the mountain–water forest also showed different attention restoration effects, with F7 performing the best. This could be because F7 has a unique natural landscape, providing visitors with a more immersive environment, thus facilitating attention restoration. On the other hand, F1, as an entrance area, may require visitors to disperse more attention to the surrounding environment due to the heavy traffic flow, resulting in its restoration effect being lower than that of other sample sites;
- The analysis of sample sites in the waterfront forest shows that while the attention restoration effects of all sample sites are not much different overall, the score of X7 is significantly higher than that of X4. The natural environment of X7 is beautiful, and its rich natural sounds and the combined effect of the landscape may have had a positive impact on the attention restoration of visitors. On the other hand, X4, as a main traffic route in the forest, may have been affected by its high traffic flow and noise level, affecting the attention restoration of visitors;
- In summary, the sample sites in the three forests show different effects in promoting the attention restoration of visitors, and these differences may be related to factors such as the natural characteristics of the site, canopy cover, noise levels, and pedestrian density.

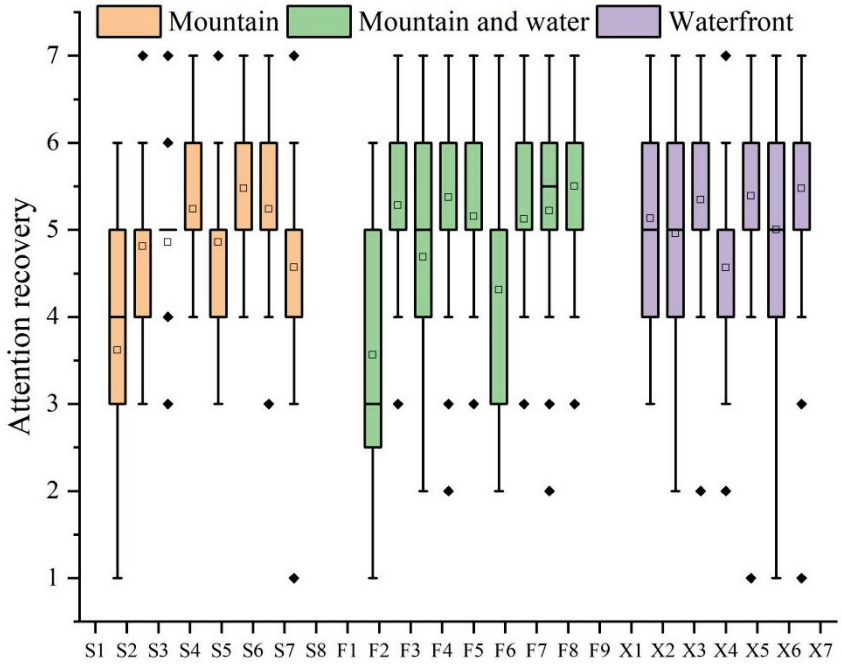



**Figure 25.** Comparative analysis of attention recovery in sample sites. Note: ◆ mild outlier.

### *3.4. Regression Analysis between Sensory Elements and the Public's Physiological and Psychological Responses*

According to the standardized regression coefficient results presented in Table 10, we can summarize some meaningful findings. Firstly, the impact of the acoustic environment on physiological and psychological indicators exhibits a complex pattern. Certain sounds, such as children's laughter, airplane noise, and the sound of mowing, can increase the body's level of physiological arousal and elevate the skin conductance response value, and this could be because these sounds are perceived as stressors or unpleasant. In contrast, other sounds, such as footsteps and sweeping, may have the opposite effect, reducing the state of physiological activation, and this could be because these sounds are perceived as innocuous or pleasant. Notably, there is a correlation between broadcast sounds and heart rate (HR), potentially increasing an individual's stress level, as they are often associated with uncertain or important information. In comparison, the sound of water is not only associated with a lower LF/HF ratio but may also lead to positive psychological experiences, such as enhancing mental vitality, alleviating stress, and restoring attention, as water is often perceived as calming and restorative.

Secondly, the characteristics of vegetation in the visual environment have a significant impact on psychological experiences. The diversity of plant layers is significantly positively correlated with positive psychological experiences, such as enhanced mental vitality, stress relief, emotional calming, and attention restoration, and this could be because vegetation diversity provides a more complex and engaging environment, which can promote exploration and cognitive functioning. This result supports a wealth of prior research on the role of visual exposure to vegetation in promoting individual psychological health [29]. However, the richness of plant color is significantly negatively correlated with positive psychological experiences, such as stress relief, emotional calming, and attention restoration; this could be because too much plant color richness can be overwhelming or distracting. Another noteworthy finding is that the higher the level of scene clutter, the worse an individual's ability to relieve stress, calm emotions, and restore attention, and this could be because scene clutter can be overwhelming or difficult to process.

**Table 10.** Standardized regression coefficients between different audio–visual environmental indicators and physiological–psychological indicators.

| | EDA | HR | LF/HF | Spiritual Vitality | Stress Relief | Emotional Arousal | Attention Recovery |
|---|---|---|---|---|---|---|---|
| Conversation | - | - | - | - | - | - | - |
| Children's laughter | 0.09 * | - | - | - | - | - | - |
| Footsteps | −0.154 ** | - | −0.448 * | - | −0.064 * | −0.063 * | −0.062 * |
| Traffic | - | - | - | - | - | - | - |
| Aircraft | 0.201 * | - | - | −0.092 * | - | - | - |
| Construction | - | - | - | - | - | - | - |
| Lawn mower | 0.182 ** | - | - | - | - | - | - |
| Sweeping | −0.164 * | - | - | - | - | - | - |
| Public announcements | - | −0.449 * | - | - | - | - | - |
| Music | - | - | - | - | - | - | - |
| Wind | - | - | - | - | - | - | - |
| Wind blowing the leaves | - | - | - | - | - | - | - |
| water | - | - | −0.359 * | 0.084 ** | 0.08 ** | 0.077 ** | 0.071 ** |
| Bird call | - | - | - | - | - | - | - |
| Insect call | - | - | - | - | - | - | - |
| Plant proportion | - | 0.17 ** | - | - | - | - | - |
| Plant color | - | - | - | - | −0.504 ** | −0.465 ** | −0.454 ** |
| Plant layers | - | - | - | 0.245 * | 0.361 ** | 0.275 * | 0.261 * |
| Skyward proportion | - | −0.807 * | - | - | - | - | - |
| Ground proportion | - | −0.769 * | - | - | - | - | - |
| Enclosure | - | −0.922 ** | - | - | - | - | - |
| Structure proportion | × | × | × | × | × | × | × |
| Pavement presence | - | - | 3.224 * | −0.455 ** | −0.506 ** | −0.565 ** | −0.581 ** |
| Scene complexity | - | 3.132 ** | - | - | −0.271 * | −0.293 * | −0.264 * |
| Water proportion | - | −0.775 * | - | 0.09 * | 0.111 * | 0.128 ** | 0.13 ** |
| Water presence | - | - | - | - | - | - | - |

Note: * and ** denote $p < 0.05$ and $p < 0.01$, respectively. - indicates that the audio–visual environment had no significant relationship with physiological–psychological indicators. × indicates that the metrics were not considered in the final model.

Lastly, the openness of the environment and the characteristics of water bodies are also important factors affecting an individual's physiological and psychological responses. For instance, a higher degree of environmental enclosure, larger sky-to-ground ratios, and other factors may trigger higher levels of physiological stress, as they can restrict an individual's field of view and freedom of movement. While the presence of pavements, the proportion of water areas, and so on, are significantly associated with the LF/HF ratio and psychological experience indicators, such as attention restoration, this could be because these factors influence an individual's spatial experience and connection with nature, thereby affecting their physiological and psychological states. These findings provide valuable insights for future environmental design optimization to improve human health conditions.

## 4. Discussion

### *4.1. The Combined Effect of Visual–Acoustic Environment on the Public's Physiology and Psychology*

The results of this study support the Stress Recovery Theory (SRT) [30] and Attention Restoration Theory (ART) [31] in environmental psychology, both of which emphasize the significant role of natural environments in restoring mental health and improving attention. Through quantitative analysis, we found that urban forests, especially waterfront forests, have a significant effect on reducing stress levels and improving mood, which is consistent with the findings of Qiu's team (2021) [32]. They pointed out that natural environments can serve as a "psychological refuge", helping individuals recover from cognitive fatigue.

A further literature review reveals the potential health impacts of different types of urban forests (such as mountain forests, waterfront forests, etc.) in various regions

around the world. These studies typically report positive psychological and physiological health benefits [33–38]. For example, a study by Hartig et al. (1991) [39] showed that regular contact with forests and other natural environments can significantly reduce stress and overall symptoms of poor health. This further confirms our findings that the visual and auditory elements of natural environments are significantly related to improving the physiological and mental health of the public. In line with our findings, mountain forests, characterized by their unique topography and vegetation, may offer enhanced psychological restoration benefits. These forests are often characterized by tranquility and remoteness from urban noise and disturbances, thereby facilitating greater stress reduction for visitors. In contrast, waterfront forests are particularly significant for psychological restoration due to their open vistas and the natural sounds of water bodies. Water bodies not only provide cooling environmental benefits but also enhance the aesthetic value and diversity of the surroundings. Additionally, the sounds of water can act as a natural white noise, masking urban noise pollution, while the visual effects of water reflections and light patterns provide additional relaxation. Hence, waterfront forests can offer even more profound stress reduction and psychological restoration experiences.

Furthermore, the impact of disturbances cannot be overlooked. Studies have shown that the restorative benefits of forests can be compromised by anthropogenic disturbances such as high visitor traffic and noise pollution. Therefore, it is crucial to consider the minimization of such disturbances in the design of forest entrances and along major walking trails. For example, buffer zones can be established to reduce the intrusion of external noise, or trail designs can be adjusted to avoid direct entry from noisy urban areas into the serene forest environment.

In terms of methodology, this study employed multiple regression analysis to quantitatively assess how different types of urban forests impact mental health indicators, ensuring the rigor of the analysis [40]. However, we also recognize certain limitations of this study, such as the limitation of sample size and the seasonal impact of data collection, which may affect the universal applicability of the results.

Based on these findings, we recommend that urban planners and landscape architects prioritize increasing vegetation coverage and water bodies while minimizing noise pollution when designing urban green spaces. This will not only provide a tranquil resting environment but also promote the psychological recovery and physiological health of residents.

### *4.2. Shortcomings and Prospects*

This study also has some limitations. First, the sample size is mainly concentrated in three forests in Fuzhou, which may not fully represent other regions or types of urban forests. Second, the study mainly focuses on the physiological and psychological responses in the short term, and future research could explore the effects of long-term exposure to these environments. Finally, the study mainly relies on self-report questionnaires, which may be subject to subjectivity, and these findings could be verified by more extensive survey methods in the future.

Future research could explore the responses of groups with different cultural backgrounds, ages, and genders to the audiovisual environment of urban forests and how to meet the needs of different groups through design. In addition, other aspects of urban forests, such as community engagement, educational programs, and recreational activities, could be studied, and how they interact with the park's audiovisual environment to jointly promote the health and well-being of the public. Through these studies, we can better understand the complex role of urban forests and provide guidance for creating healthier and more sustainable urban environments.

## 5. Conclusions

This study was conducted in three different types of urban forests in Fuzhou City, systematically assessing the impact of the visual–acoustic environment of urban forests

on the physiological and psychological well-being of the public and making a significant contribution to the scientific research and practical application of urban forests. Our findings clearly indicate that natural elements in urban forests have a markedly positive effect on enhancing residents' mental health and physiological relaxation. This discovery is of great importance for guiding the design and management of urban forests.

Our research emphasizes the need to prioritize the integration of natural elements in urban forest planning, such as vegetation, water bodies, and natural soundscapes, to promote psychological recovery and stress relief for residents. Furthermore, our study provides a basis for the classified management of urban forests, revealing the differences in providing psychological and physiological benefits among various types of urban forests. This helps decision-makers and planners to develop more precise management strategies based on the specific characteristics of the forests.

Through this study, we provide empirical support for the potential benefits of urban forests to public health, which is significant for promoting the role of urban forests in enhancing the quality of urban life. Future research can further explore the differentiated impacts of urban forests on different population groups and how innovative urban forest designs can meet a broader range of social needs. Our work provides a scientific foundation and practical guidance for achieving a greener, healthier, and more sustainable urban living environment.

**Author Contributions:** Conceptualization, Y.L., J.D. and Y.C.; methodology, Y.L., J.D. and Y.C.; software, Y.L., Y.T., Z.L., X.Y., Z.Z., F.L. and Y.C.; validation, Y.L., Y.T., X.Y., Z.Z., F.L., J.D. and Y.C.; formal analysis, Y.L., Y.T., J.L. and Y.C.; investigation, Y.L., X.Y., Z.Z., F.L., J.L., J.D. and Y.C.; resources, Y.L., Z.L., X.Y., Z.Z., F.L., J.L., J.D. and Y.C.; data curation, Y.L., Z.L. and Y.C.; writing—original draft preparation, Y.L., Y.T., Z.L. and J.D.; writing—review and editing, Y.L., X.Y., Z.Z., F.L., J.L., J.D. and Y.C.; visualization, Y.L., X.Y., Z.Z., F.L. and J.L.; supervision, Y.L., Y.T. and J.L.; project administration, Y.L. and J.L.; funding acquisition, Y.L. and J.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Education Department of Fujian Province, grant number JAT220221 and the Fujian University of Technology, grant number GY-Z220213.

**Data Availability Statement:** The data used to support the findings of this study are available from the corresponding author upon request.

**Acknowledgments:** We would like to express our sincere gratitude to Beijing KingFar International Inc for their generous support through the "Scientific Research Support Program". We are particularly grateful to the project team's research staff for their invaluable technical support and providing access to the ErgoLAB research equipment. Their contributions have significantly enhanced our research capabilities and have made this project possible. We are deeply appreciative of their generosity and support.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Yilmaz, T.; Savkli, F. Effects of the use of water features in antalya urban parks. *J. Environ. Prot. Ecol.* **2014**, *15*, 1603–1609.
2. Chen, C.D.; Lu, Y.; Jia, J.S.; Chen, Y.; Xue, J.H.; Liang, H.H. Urban spontaneous vegetation helps create unique landsenses. *Int. J. Sustain. Dev. World Ecol.* **2021**, *28*, 593–601. [CrossRef]
3. Ebbensgaard, C.L. 'I like the sound of falling water, it's calming': Engineering sensory experiences through landscape architecture. *Cult. Geogr.* **2017**, *24*, 441–455. [CrossRef]
4. Li, S.Y.; Chen, Z.; Guo, L.H.; Hu, F.B.; Huang, Y.J.; Wu, D.C.; Wu, Z.G.; Hong, X.C. How do spatial forms influence psychophysical drivers in a campus city community life circle? *Sustainability* **2023**, *15*, 10014. [CrossRef]
5. Chen, Y.; Liu, F.; Lin, X.Y.; Liu, J.; Chen, Z.Y.; Shi, K.L.; Li, J.Y.; Dong, J.W. Combined Effects of the Thermal-Acoustic Environment on Subjective Evaluations in Urban Park Based on Sensory-Walking. *Forests* **2023**, *14*, 1161. [CrossRef]
6. Hedblom, M.; Gunnarsson, B.; Iravani, B.; Knez, I.; Schaefer, M.; Thorsson, P.; Lundström, J.N. Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Sci. Rep.-UK* **2019**, *9*, 10113. [CrossRef] [PubMed]
7. Hasegawa, Y.; Lau, S.K. Audiovisual bimodal and interactive effects for soundscape design of the indoor environments: A systematic review. *Sustainability* **2021**, *13*, 339. [CrossRef]

8. Agnieszka Jaszczak, E.P.K.K. Redefinition of park design criteria as a result of analysis of Well-Being and soundscape: The case study of the kortowo park (Poland). *Int. J. Environ. Res. Public Health* **2021**, *18*, 2972. [CrossRef] [PubMed]
9. Chen, Y.; Chen, Z.Y.; Lin, S.M.; Lin, X.Q.; Li, S.T.; Li, T.Y.; Dong, J.W. Thermal-Acoustic Interaction Impacts on Crowd Behaviors in an Urban Park. *Forests* **2023**, *14*, 1758. [CrossRef]
10. Liu, B. The objective indicating of landscape architecture subjective perception: The objective information translation principle of digitization and quantitative evaluation of visual perception for landscape architecture. *Chin. Landsc. Archit.* **2015**, *31*, 6–9.
11. van der Zanden, E.H.; Verburg, P.H.; Mücher, C.A. Modelling the spatial distribution of linear landscape elements in Europe. *Ecol. Indic.* **2013**, *27*, 125–136. [CrossRef]
12. Fang, Y.L.; Que, Q.M.; Tu, R.X.; Liu, Y.J.; Gao, W. How do landscape elements affect public health in subtropical high-density city: The pathway through the neighborhood physical environmental factors. *Build. Environ.* **2021**, *206*, 108336. [CrossRef]
13. Lin, W.Y.; Mu, Y.X.; Zhang, Z.; Wang, J.; Diao, X.L.; Lu, Z.J.; Guo, W.C.; Wang, Y.; Xu, B. Research on cognitive evaluation of forest color based on visual behavior experiments and landscape preference. *PLoS ONE* **2022**, *17*, e0276677. [CrossRef] [PubMed]
14. Hirt, U.; Mewes, M.; Meyer, B.C. A new approach to comprehensive quantification of linear landscape elements using biotope types on a regional scale. *Phys. Chem. Earth* **2011**, *36*, 579–590. [CrossRef]
15. Yu, X.Y.; Liu, C.J. Planning and design of park plant landscape based on the vision of urban ecological environment. *Fresen. Environ. Bull.* **2022**, *31*, 1979–1988.
16. Lee, J.; Park, B.J.; Ohira, T.; Kagawa, T.; Miyazaki, Y. Acute Effects of Exposure to a Traditional Rural Environment on Urban Dwellers: A Crossover Field Study in Terraced Farmland. *Int. J. Environ. Res. Public Health* **2015**, *12*, 1874–1893. [CrossRef] [PubMed]
17. Posada-Quintero, H.F.; Chon, K.H. Innovations in electrodermal activity data collection and signal processing: A systematic review. *Sensors* **2020**, *20*, 479. [CrossRef]
18. Zhao, R.L.; Zhang, G.; Wang, X.; Zhang, B.T.; Guo, L.N.; Niu, L.X.; Zhang, Y.L. Psycho-Physiological effects of a Peony-Viewing program on Middle-Aged and elderly individuals at different phenological stages. *Int. J. Environ. Res. Public Health* **2019**, *16*, 439. [CrossRef] [PubMed]
19. Sacha, J.; Barabach, S.; Statkiewicz-Barabach, G.; Sacha, K.; Müller, A.; Piskorski, J.; Barthel, P.; Schmidt, G. Gender differences in the interaction between heart rate and its variability—How to use it to improve the prognostic power of heart rate variability. *Int. J. Cardiol.* **2014**, *171*, E42–E45. [CrossRef]
20. Farah, B.Q.; Barros, M.V.G.; Balagopal, B.; Ritti-Dias, R.M. Heart rate variability and cardiovascular risk factors in adolescent boys (Article). *J. Pediatr. USA* **2014**, *165*, 945–950. [CrossRef]
21. Nasoz, F.; Lisetti, C.L.; Alvarez, K.; Finkelstein, N. Emotion Recognition from Physiological Signals for User Modeling of Affect. In Proceedings of the 3rd Workshop on Affective and Attitude User Modelling, Pittsburgh, PA, USA, 22–26 June 2003.
22. Scheirer, J.; Fernandez, R.; Klein, J.; Picard, R.W. Frustrating the user on purpose: A step toward building an affective computer—ScienceDirect. *Interact. Comput.* **2002**, *14*, 93–118. [CrossRef]
23. Peter, C.; Herbon, A. Emotion representation and physiology assignments in digital systems. *Interact. Comput.* **2006**, *18*, 139–170. [CrossRef]
24. Song, C.; Ikei, H.; Igarashi, M.; Miwa, M.; Takagaki, M.; Miyazaki, Y. Physiological and psychological responses of young males during spring-time walks in urban parks. *J. Physiol. Anthropol.* **2014**, *33*, 8. [CrossRef] [PubMed]
25. Jiang, L.; Ling, Y.; Likun, H.; Architecture, S.O.; University, F. Research on the influential factors of soundscape experience in urban ecological park. *Landsc. Archit.* **2019**, *26*, 89–93.
26. Xing, Q.X.; Sun, H.; Guan, B.; Zheng, J.F. The satisfaction of free park visitors in xi'an based on fuzzy comprehension evaluation. *Resour. Sci.* **2014**, *36*, 1645–1651.
27. Shao, T.; Yang, P.; Jiang, H.; Shao, Q. An analysis of public service satisfaction of tourists at scenic spots: The case of xiamen city. *Sustainability* **2023**, *15*, 2752. [CrossRef]
28. Kaplan, R.; Kaplan, S. *Humanscape: Environments for People*; Princeton University Press: Princeton, NL, USA, 1982.
29. Southon, G.E.; Jorgensen, A.; Dunnett, N.; Hoyle, H.; Evans, K.L. Perceived species-richness in urban green spaces: Cues, accuracy and well-being impacts. *Landsc. Urban Plan.* **2018**, *172*, 1–10. [CrossRef]
30. Gaekwad, J.S.; Moslehian, A.S.; Roös, P.B. A meta-analysis of physiological stress responses to natural environments: Biophilia and Stress Recovery Theory perspectives. *J. Environ. Psychol.* **2023**, *90*, 102085. [CrossRef]
31. Wilkie, S.; Thompson, E.; Cranner, P.; Ginty, K. Attention restoration theory as a framework for analysis of Tweets about urban green space: A case study. *Landsc. Res.* **2020**, *45*, 777–788. [CrossRef]
32. Qiu, L.; Chen, Q.J.; Gao, T. The effects of urban natural environments on preference and Self-Reported psychological restoration of the elderly. *Int. J. Environ. Res. Public Health* **2021**, *18*, 509. [CrossRef]
33. Wu, L.J.; Dong, Q.D.; Luo, S.X.; Jiang, W.Y.; Hao, M.; Chen, Q.B. Effects of spatial elements of urban landscape forests on the restoration potential and preference of adolescents. *Land* **2021**, *10*, 1349. [CrossRef]
34. Rathmann, J.; Beck, C.; Flutura, S.; Seiderer, A.; Aslan, I.; André, E. Towards quantifying forest recreation: Exploring outdoor thermal physiology and human well-being along exemplary pathways in a central European urban forest (Augsburg, SE-Germany). *Urban For. Urban Green.* **2020**, *49*, 126622. [CrossRef]
35. Hauru, K.; Lehvävirta, S.; Korpela, K.; Kotze, D.J. Closure of view to the urban matrix has positive effects on perceived restorativeness in urban forests in Helsinki, Finland. *Landsc. Urban Plan.* **2012**, *107*, 361–369. [CrossRef]

36. Hong, X.C.; Cheng, S.; Liu, J.; Guo, L.H.; Dang, E.; Wang, J.B.; Cheng, Y.N. How Should Soundscape Optimization from Perceived Soundscape Elements in Urban Forests by the Riverside Be Performed? *Land* **2023**, *12*, 1929. [CrossRef]
37. Hong, X.C.; Liu, J.; Wang, G.Y. Soundscape in Urban Forests. *Forests* **2022**, *13*, 2056. [CrossRef]
38. Guo, L.H.; Cheng, S.; Liu, J.; Wang, Y.Y.; Cai, Y.S.; Hong, X.C. Does social perception data express the spatio-temporal pattern of perceived urban noise? A case study based on 3,137 noise complaints in Fuzhou, China. *Appl. Acoust.* **2022**, *201*, 109129. [CrossRef]
39. Hartig, T.; Mang, M.; Evans, G.W. Restorative effects of natural environment experiences. *Environ. Behav.* **1991**, *23*, 3–26. [CrossRef]
40. Fleming, A.; Steenberg, J. The equity of urban forest change and frequency in Toronto, ON. *Urban For. Urban Green.* **2023**, *90*, 128153. [CrossRef]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

*Article*

# Exploring the Relationship between the Sentiments of Young People and Urban Green Space by Using a Check-In Microblog

**Jing Zhang [1,†], Liwen Liu [1,†], Jianwu Wang [2], Dubing Dong [1], Ting Jiang [1,*], Jian Chen [1,2] and Yuan Ren [1,*]**

[1] State Key Laboratory of Subtropical Silviculture, Zhejiang A&F University, Hangzhou 311300, China; zhangjing@stu.zafu.edu.cn (J.Z.); liwenliu16@gmail.com (L.L.); dongdubin@gmx.com (D.D.); chenjian@zafu.edu.cn (J.C.)

[2] Zhejiang Forest Resource Monitoring Center, Hangzhou 310020, China; jianwuwang1986@aliyun.com

* Correspondence: lxyjt@zafu.edu.cn (T.J.); renyuan@zafu.edu.cn (Y.R.)

† These authors contributed equally to this work.

**Abstract:** Green spaces have a positive impact on the mood of urban residents. However, previous studies have focused primarily on parks or residential areas, neglecting the influence of green spaces in different socioeconomic locations on public sentiment. This oversight fails to acknowledge that most young individuals are exposed to places beyond their homes and parks throughout the day. Using web crawlers, we collected 105,214 Sina Weibo posts from 14,651 geographical check-in points in Hangzhou, Zhejiang Province. We developed a mixed ordered logistic regression model to quantify the relationship between public sentiment (negative/neutral/positive) and the surrounding green space. The findings are as follows: (1) the correlation between GVI and public sentiment is stronger than that between public sentiment and NDVI; (2) among different socioeconomic regions, residential areas are associated with lower levels of public sentiment, while parks are associated with higher levels; and (3) at a scale of 1000 m, an increase of 1% in GVI significantly improves public sentiment regarding transportation hubs, with a regression coefficient of 0.0333. The relationship between green space and public sentiment is intricate and nuanced, and it is influenced by both public activities and spatiotemporal contexts. Urban green space planners should consider additional factors to enhance the effectiveness of green space in improving public sentiment.

**Keywords:** urban green space; social media; sentiment; GVI; NDVI

**Citation:** Zhang, J.; Liu, L.; Wang, J.; Dong, D.; Jiang, T.; Chen, J.; Ren, Y. Exploring the Relationship between the Sentiments of Young People and Urban Green Space by Using a Check-In Microblog. *Forests* **2024**, *15*, 796. https://doi.org/10.3390/f15050796

Academic Editor: Zhibin Ren

Received: 12 March 2024
Revised: 19 April 2024
Accepted: 29 April 2024
Published: 30 April 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

In the context of global urbanization, it is projected that the urban population will surpass 60% of the total population by 2050 [1]. As cities expand due to population influx, natural landscapes such as forests, grasslands, and wetlands are gradually being replaced by impermeable surfaces, such as concrete and asphalt [2], thereby limiting opportunities for urban residents to engage with nature. This urban lifestyle results in reduced public interaction with the natural environment and can have detrimental effects on mental health, including depression, anxiety, and loneliness [3]. Young individuals in China face a particularly high risk of depression. According to the China Emotional Health Development Report (2021–2022), the prevalence of depression among individuals aged 18–24 and 25–34 is significantly greater than that among individuals aged 35 and older [4].

An increasing body of research indicates that exposure to green spaces is associated with mental health benefits for urban residents [5], as well as a reduced risk of certain types of mental illnesses in the general population [6]. Studies investigating the relationship between greening and mental health rely only on remote sensing data and may not accurately capture the level of public perception of greenery [7,8]. Green view index (GVI) has been proposed as a more suitable measure for capturing public perceptions of green spaces, with previous studies confirming a close relationship through physiological measures [9], questionnaires [10], and GPS activity diaries [10]. However, comparative studies examining

the impact of GVI and normalized difference vegetation index (NDVI) on public sentiment are still lacking, given the limitations of traditional methods, namely their passive and static characteristics and small sample sizes [11,12].

In urban areas, the public receives natural and cultural ecosystem services from nearby green spaces through various mechanisms [13]. Biophilicity-derived stress reduction theory (SRT) [14] and attention restoration theory (ART) [15] suggest that natural environments meet the psychological needs of the public; in addition, physical activity [16], social interaction [17], and environmental regulation [18] may also mediate psychological benefits. Inequities in access to green spaces remain [19]. Previous studies on green spaces and health have proposed improvement strategies for residential and park green spaces aimed at vulnerable groups, such as elderly people and young children [20,21]. However, most young adults face greater work-life pressures [22], and their little available leisure time [23] significantly affects their activities in residential and park green spaces. Additionally, the attractiveness of green space quality [24,25] and epidemic lockdowns [26] also affect public access to green spaces.

Social media is commonly regarded as an active platform for younger people to express themselves [11]. Previous research utilizing social media data to analyze public sentiment towards green spaces has predominantly focused on green park areas [12,24,27–29] or residential areas [29]. For instance, sentiments expressed in parks located outside Manhattan in New York City were found to be greater than those expressed in internally located parks [28]; inadequate cleanliness reduces the utilization of green spaces by the public [29]; and visitors' sentiments towards comprehensive and heritage parks were significantly more positive than those towards community parks [27]. These studies have validated the utility of geotagged social media data for investigating the relationship between public sentiment and urban green spaces.

Recent research has substantiated disparities in public sentiment across diverse environments, with individuals exhibiting greater happiness levels in natural landscapes than in densely urbanized areas [30]. Furthermore, the influence of tree canopy coverage on public sentiment varies depending on the type of land use and the urban functional zone [12]. Notably, vague functional zones and land use categories offer limited insights into location backgrounds, as most adults tend to visit destinations associated with socioeconomic factors. Consequently, acknowledging the significance of the impact of green spaces on public sentiment among different socioeconomic contexts is crucial; however, no comparative studies have been undertaken thus far.

Therefore, in this paper, we rely on geographically located Weibo texts as data sources and incorporate data from multiple sources, such as street view, remote sensing, weather, and air quality, to study the relationship between public sentiment and green spaces. We employ a logistic regression model to quantify the association between green space and public sentiment while considering multiple covariates. We present three questions: (1) Are the green space indicators GVI and NDVI related to public sentiment? (2) Do different types of socioeconomic locations exhibit variations in public sentiment? (3) Do green spaces surrounding different socioeconomic locations have different impacts on the sentiments of young people?

## 2. Materials and Methods

### 2.1. Study Area

Hangzhou is located in the Yangtze River Delta region (29°11′ N to 30°33′ N, 118°21′ E to 120°30′ E) (Figure 1). It is an internationally renowned tourist city with developed financial services, e-commerce, and information technology. In 2023, the total population of Hangzhou exceeded 10 million, with a population density of nearly 2800 people per square kilometer. The study area has undergone rapid urbanization, leading to the significant conversion of natural landscapes for urban expansion and substantial changes in the built environment [31]. As a result, the lifestyles and psychological well-being of many urban residents have undergone dramatic transformations.

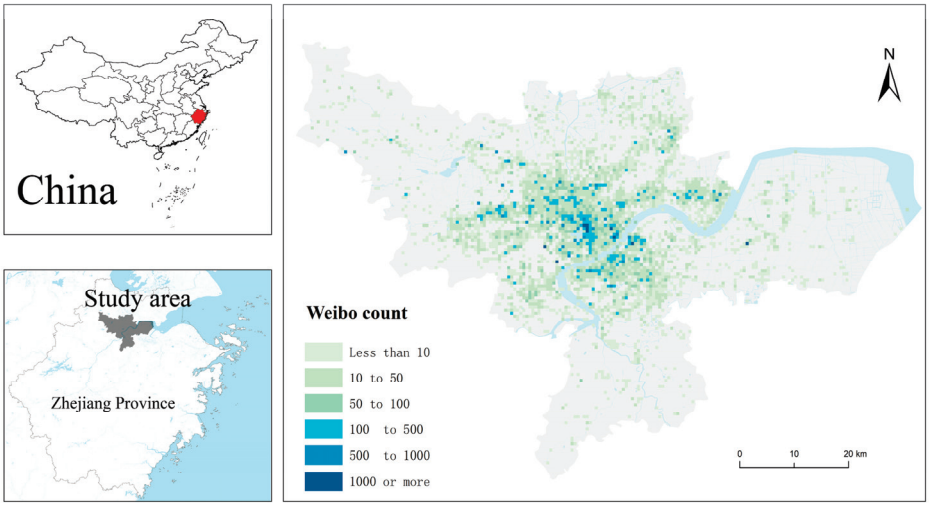



**Figure 1.** Location of the study area and spatial distribution of Weibo accounts in the sample.

### *2.2. Study Samples*

In this study, web crawlers were employed to collect the required social media data. Web crawling is a technique that mimics browser access to online resources. It automatically gathers necessary data from one or more pages using specific strategies. The raw check-in data of Weibo in the selected research area are encoded in JSON (JavaScript Object Notation) format. To facilitate statistical analysis, we used Python scripts to extract key fields, including user ID, Post ID, text content, creation time, longitude and latitude, Weibo link, location name, and location type. Then, we stored the data in comma-separated value (CSV) format. After removing data outside the geographical scope of the research area and conducting text cleaning, we deleted duplicate Weibo posts, non-Chinese Weibo posts, empty expressions, and text with imprecise geographic locations [29,32]. Next, we excluded Weibo posts sent by robots, such as advertisements and weather reports [12]. Ultimately, 128,639 geotagged Weibo posts from 16,257 check-in locations were collected (Figure 1). Finally, to investigate the correlation between the sentiment of the public and the surrounding environments, we further removed check-in locations that are not in the Baidu Street View data distribution range. The data analysis was conducted on 105,214 geotagged Weibo posts sent from 14,651 geographical check-in locations in Hangzhou, Zhejiang Province, China, during the period from 1 August 2022 to 31 August 2023.

### *2.3. Data Acquisition*

Sentiment classification. To extract the sentiment category of each Weibo image based on its content, we utilized the text sentiment analysis provided by the Baidu Natural Language Processing (NLP) platform (https://ai.baidu.com/tech/nlp, accessed on 8 October 2023) (Figure 2), which is one of the first four national new generation artificial intelligence open innovation platforms approved by the Ministry of Science and Technology of China in 2017. In the sentiment analysis for Weibo, Chinese characters are first extracted to construct Chinese word segments, and the sentiment scores of these word segments are obtained from Baidu words (https://cloud.baidu.com/doc/API/index.html, accessed on 8 October 2023) that contain sentiment scores for Chinese words. Using this technique, the sentiment polarity category (negative/neutral/positive) of the text can be automatically determined [33]. Like the English natural language processing toolkit TextBlob, the Baidu Natural Language Processing (NLP) platform is a powerful Chinese text processing library.

NDVI measurements (Figure 3a). NDVI is a satellite-based vegetation index used to quantify urban greenness. We selected cloud-free images covering the survey area and then identified a satellite image with a resolution of 30 meters taken by the Landsat 8 Operational Land Imager (OLI) on 12 June 2023. The obtained images underwent

radiometric calibration, geometric correction, and atmospheric correction (Figure 2). The NDVI value is calculated using reflectance data from two electromagnetic spectrum bands, Landsat band 4 (near infrared) and Landsat band 3 (red), with values ranging from −1 to 1, where positive values indicate more vegetation. In our study, negative values representing water and bare soil were adjusted to 0 so that NDVI values would not cancel out positive normalized vegetation index values when averages are calculated [34]. Here, *RED* and *NIR* represent the spectral reflectance measurements obtained in the red and near-infrared regions, respectively. *NDVI* is calculated as follows:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

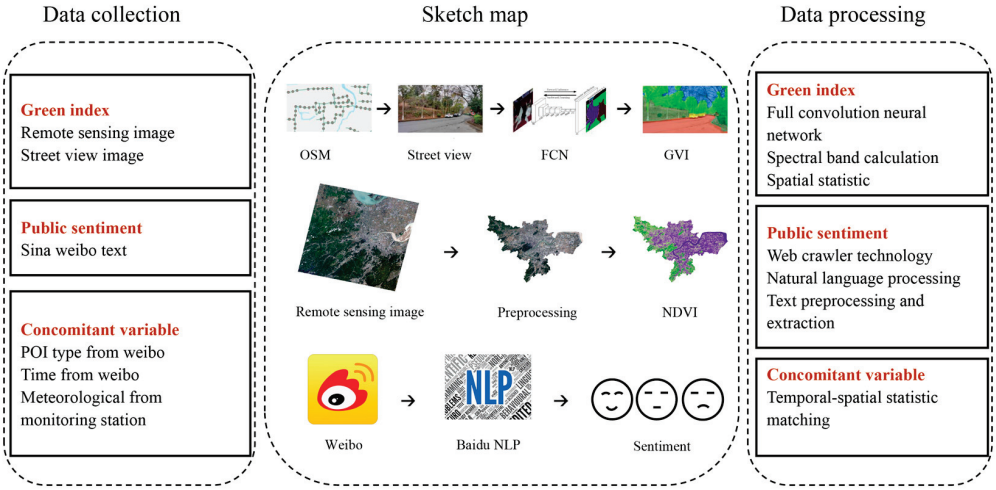



**Figure 2.** Data acquisition process.

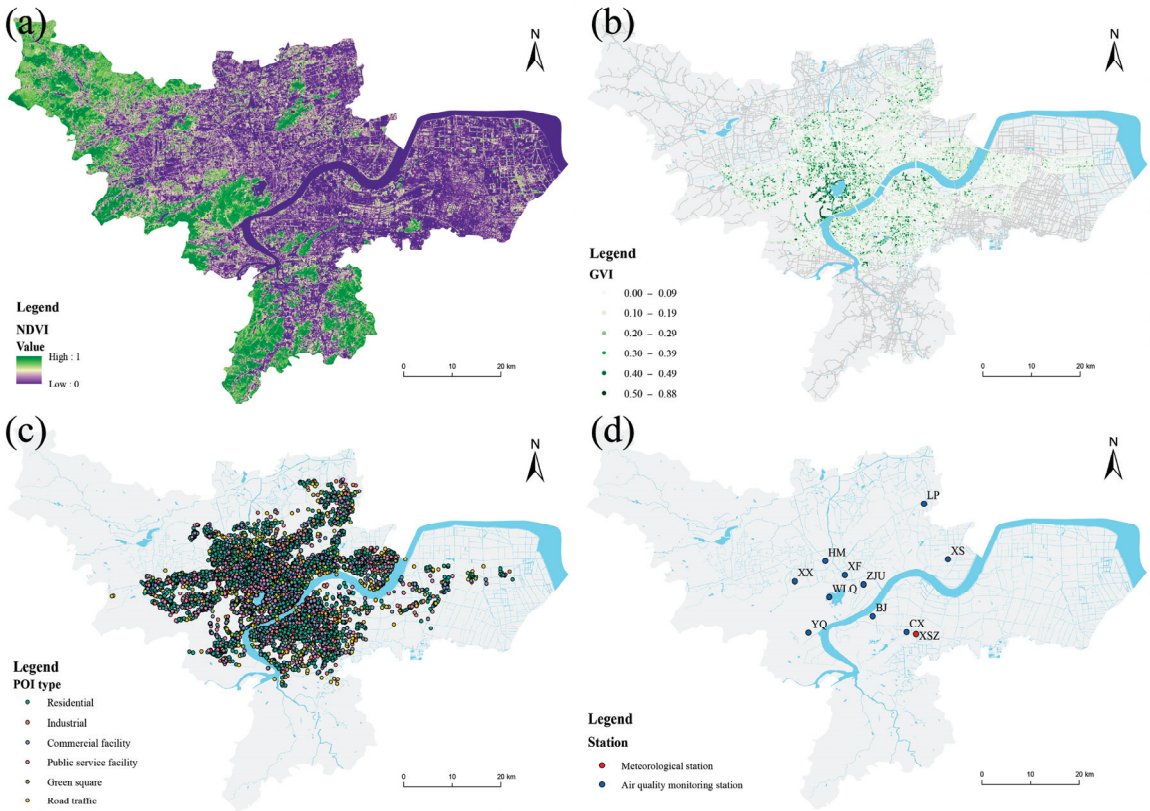



**Figure 3.** (**a**) Spatial distribution of NDVI, (**b**) Spatial distribution of GVI, (**c**) Spatial distribution of Weibo check-in points' POI types, (**d**) Weather monitoring site distribution.

GVI measurements (Figure 3b). GVI refers to the quantity of greenery that can be visually perceived from a specific location. It is identified by extracting green vegetation pixels from street view images using Baidu Online Maps. Road network data are obtained from OpenStreetMap (OSM) (https://www.openstreetmap.org, accessed on 1 September 2023), and the road network data are intersected with the buffer zone expanded from the check-in point position using ArcGIS 10.8 (Esri, Redlands, CA, USA) to obtain the surrounding road network. Sampling points are generated at an equal interval of 100 m along the road, and the coordinates of the generated points are input into a Python script obtained using an application programming interface (API). One point collects four static images of street view at horizontal angles of 0°, 90°, 180°, and 270° [29]. The above data were collected in October 2023, Baidu Maps provided street view data for June 2022, and the OSM platform provided road network data for 2021. Since some sampling points may return null values, these sampling points were deleted. A total of 193,868 street view images from 48,467 point locations were ultimately retained. Image semantic segmentation is a cornerstone technology for image understanding and an important task in the computer vision field. Many high-quality open-source frameworks are available for use. Fully convolutional networks (FCNs) are commonly used for the semantic segmentation of street view images. The existing FCN models can recognize up to 150 street view elements [35]. In this study, we use street view images to identify plant features through a well-trained FCN model, which exhibits an average estimation accuracy of over 90% [35]. According to research needs, we take the proportion of vegetation category pixels as GVI (Figure 2).

In addition to the main predictive factors of interest, we also include several covariates, which may help us adjust the relationship between public sentiment and green spaces. These data are divided into three groups: location type, weather conditions, and time. These variables have been found to be closely related to sentiment based on social media text data in previous studies [12,33,36], so we include them as covariates. For location type, we use point of information (POI) data, including cognitive and conceptual POIs [37]. These data can explain the socioeconomic attributes of human activities [38], comprehensively reflecting the socioeconomic activity background behind them by using Weibo POI data for urban functional zoning [39]. Therefore, by using the geolocation and POI types of Weibo, we can objectively reveal the activity background of public sentiment expression at each check-in place to a certain extent. For the convenience of this research, we reclassified the POI data of Weibo into six categories based on the national land classification standard (Figure 3c) and the national economic industry classification [40], with each category containing several subcategories. For weather conditions, we used four covariates: temperature, dew point, rain, and $PM_{2.5}$. $PM_{2.5}$ data were obtained from the national monitoring point of the air quality monitoring and analysis platform (https://www.aqistudy.cn, accessed on 9 September 2023). Other meteorological data were obtained from the National Oceanic and Atmospheric Administration (NOAA) integrated surface database. We spatiotemporally matched each located check-in on Weibo with the nearest weather station or air quality monitoring station (Figure 3d). In addition, two covariates related to time were created based on the time tags associated with each Weibo post: weekend and weekdays and day and night. The spatial data processing related to the above processes was conducted in ArcGIS 10.8.

### *2.4. Data Processing and Analytical Methods*

We considered three circular buffer zone scales of 200 m, 500 m, and 1000 m. Social media data may have potential location ambiguity, and buffer zones are believed to overcome this issue [28] However, no consensus has been reached regarding the measurement of a green space's buffer distance, and spatial–temporal uncertainty may vary by region [41]. Based on previous studies on the association between sentiment and green spaces [34,42–46], green spaces within 500 m and 1000 m buffer zones are often found to have a good correlation with public sentiment. However, considering that some studies suggest that social media

data are instantaneously expressed [12], we also used a smaller 200 m buffer zone scale to determine the relationships within it.

Previous studies on the impact of social media data and green space on public emotion mostly used *t* tests and variance significance tests. These statistical methods have certain limitations, such as the failure to consider the internal correlation between data points collected near the same place when making hypotheses [47]. And the influence of important confounding factors, such as weather conditions and time background, were also not considered. Statistical models, such as logistic regression, are gradually used to overcome such difficulties [12].

To analyze the data, we employed the Spearman correlation and constructed a linear model. Subsequently, we employed a random intercept mixed-effect ordered logistic regression model with check-in location as the random effect (Appendix A.1). Given that our sentiment data are ordinal in nature (negative/neutral/positive), an ordered discrete choice model can effectively explain the ordered characteristics of the response results. Most geotagged location samples consist of multiple texts and texts sent from the same location may not be independent due to environmental background influences, incorporating check-in locations as random effects allows us to account for unobserved heterogeneity between locations. To compare fixed-effect models and mixed-effect models (Table A1), we utilized the likelihood ratio test (LRT) and Akaike's information criterion (AIC) [48].

The model takes public sentiment as the dependent variable, and the GVI, NDVI, POI type, time factor, and meteorological factor as the fixed effect. We maintained the continuity of the main green space data. Since both NDVI and GVI data were between 0 and 1, we processed them as percentages so that each unit in our data analysis model was in the form 0.01 instead of 1. We classified other types of covariates according to previous research [12]. An overview of the data is provided in Tables A2 and A3. To explore the benefits of green spaces for public sentiment in different geographical locations, we constructed interaction terms GVI× POI type and NDVI ×POI type based on the previous random-effect ordered logistic regression model and plotted forest plots using the corresponding coefficient results. The above data analysis process was conducted using Stata 17.0 (StataCorp, College Station, TX, USA).

## 3. Results

### *3.1. Correlation Analysis of the Greening Index and Sentiment*

We selected the check-in microblog points with more than 10 messages sent and calculated the proportion of positive texts for each location as the probability of positive sentiment at that specific place. Since both the green space data and the probability of positive sentiment data deviated from a normal distribution, we employed Spearman's rank correlation to investigate the relationship between each green space indicator and the probability of positive sentiment (Figure 4a). The correlation between GVI and the probability of positive sentiment was found to be stronger than that between NDVI and the probability of positive sentiment, with GVI 1000 m exhibiting the highest correlation with the probability of positive sentiment among all GVI indicators (Figure 4b), while NDVI 200 m showed the strongest correlation with the probability of positive sentiment among all NDVI indicators (Figure 4c). Street view green space indicators demonstrated a closer association with the probability of positive sentiment when compared to remote sensing levels. Moreover, a greater degree of correlation was observed among the different GVI indicators than among the NDVI indicators. Additionally, the variation in the relationship between the GVI and probability of positive sentiment across spatial scales was smaller than that observed for the NDVI. Notably, Spearman's rank correlation indicated that the highest correlation between the NDVI and GVI occurred when both were measured within a radius of 200 m (Spearman r = 0.382).

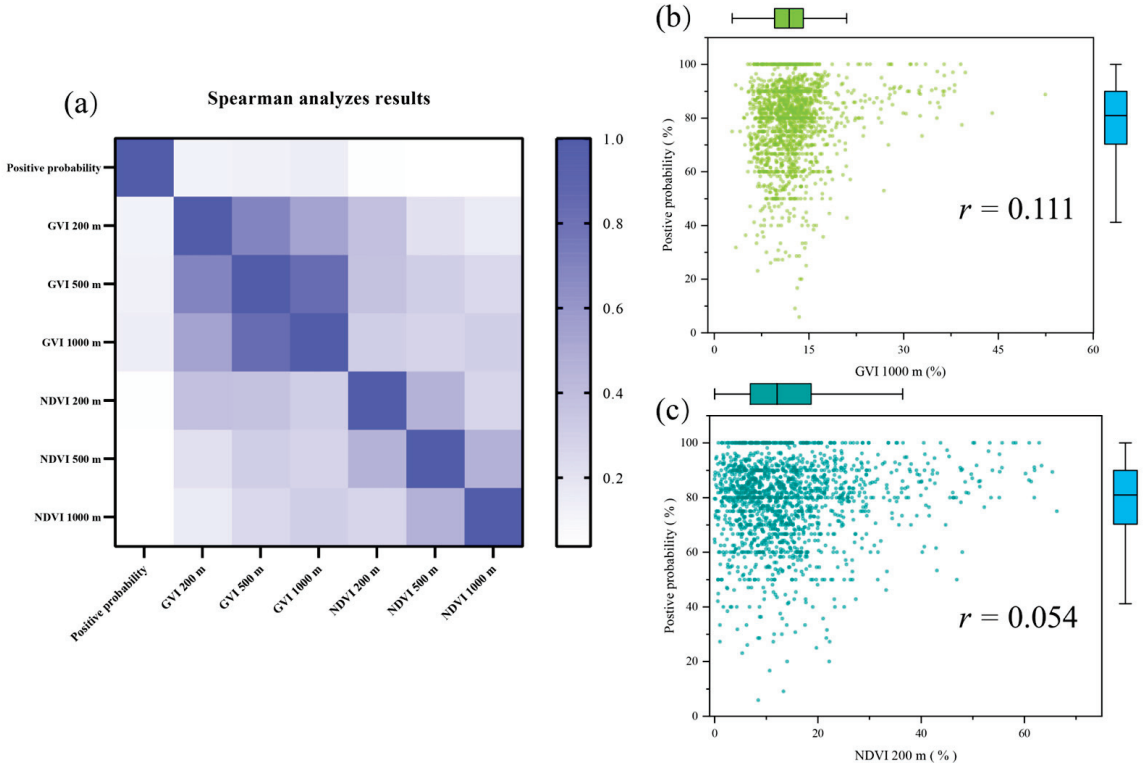



**Figure 4.** (**a**) Spearman correlation analysis results, (**b**) Scatter plot of GVI 1000 m and positive probability, (**c**) Scatter plot of NDVI 200 m and positive probability.

We also attempted to establish a linear relationship between the green space index and the probability of positive sentiment. GVI 1000 m exhibited a significant positive correlation with the probability of positive sentiment (B = 0.413). NDVI 200 m also demonstrated a significant positive correlation with the probability of positive sentiment (B = 0.112). However, importantly, the R2 values are relatively low, indicating limited explanatory power of green space in influencing public sentiment from an overall statistical effectiveness perspective. This highlights the need to further explore other potential influencing factors.

### *3.2. Effects of Greening and Related Potential Factors on Sentiment*

The coefficients of GVI and public sentiment exhibit greater magnitudes than those of NDVI and public sentiment, suggesting that GVI aligns more consistently with the public's perception of green space. Table 1 shows a significant positive correlation between the coefficients of GVI and NDVI and public sentiment at a scale of 200 m, with values of 0.0052 and 0.0044, respectively. In terms of location type, the coefficients for other socioeconomic categories are significantly greater than those for residential areas, with parks displaying the highest coefficient, followed by commercial facilities. The coefficients for public sentiment on weekdays are lower than those on weekends, but this difference lacks statistical significance; similarly, the coefficients for public sentiment on rainy days are greater than those on non-rainy days, and this difference lacks statistical significance. Moreover, the coefficients for public sentiment during the daytime are significantly greater than those observed at night. Although not statistically significant, an increase in dew point temperature is associated with a decrease in the coefficient for public sentiment; furthermore, when pollution levels exceed reference values ($\leq$35 $\mu g/m^3$), the coefficients for $PM_{2.5}$-related sentiments generally decline, except within the range of 75–115 $\mu g/m^3$, where significance is observed. Last, when compared to temperatures below freezing (<0 °C), all temperature segments display greater coefficients for public sentiment without reaching statistical significance; notably, the segment ranging from 12–18 °C exhibits the highest coefficient.

**Table 1.** Estimation results for the random-effect models.

| Characteristics | | Coefficient (95% CI) | | |
|---|---|---|---|---|
| | | 200 m | 500 m | 1000 m |
| Greening index | GVI 200 m (per 0.01 change) | 0.0052 (0.0018, 0.0086) [a] | 0.0116 (0.0069, 0.0163) [a] | 0.0178 (0.0122, 0.0234) [a] |
| | NDVI 200 m (per 0.01 change) | 0.0044 (0.0021, 0.0067) [a] | 0.0015 (−0.0006, 0.0036) | −0.0006 (−0.0026, 0.0013) |
| POI type | Residential (base) | | | |
| | Industrial | 0.3046 (0.1646, 0.4446) [a] | 0.2977 (0.1579, 0.4376) [a] | 0.294 (0.1544, 0.4337) [a] |
| | Commercial Facility | 0.5187 (0.4594, 0.578) [a] | 0.5037 (0.4442, 0.5632) [a] | 0.499 (0.4395, 0.5585) [a] |
| | Public Service Facility | 0.3812 (0.3145, 0.4479) [a] | 0.3738 (0.3071, 0.4406) [a] | 0.3711 (0.3044, 0.4378) [a] |
| | Green Square | 0.7244 (0.5903, 0.8585) [a] | 0.7242 (0.5902, 0.8582) [a] | 0.7187 (0.5849, 0.8524) [a] |
| | Road Traffic | 0.2353 (0.1304, 0.3402) [a] | 0.2318 (0.127, 0.3366) [a] | 0.2283 (0.1235, 0.333) [a] |
| Dew point (°C) | ≤2 (base) | | | |
| | 2–<16 | −0.0799 (−0.1663, 0.0065) [b] | −0.0801 (−0.1664, 0.0063) [b] | −0.0797 (−0.1661, 0.0067) [b] |
| | 16+ | −0.0953 (−0.203, 0.0124) [b] | −0.0961 (−0.2038, 0.0116) [b] | −0.0954 (−0.2032, 0.0123) [b] |
| $PM_{2.5}$ (μg/m$^3$) | ≤35 (base) | | | |
| | 35–<75 | 0.0134 (−0.03, 0.0568) | 0.014 (−0.0294, 0.0574) | 0.0139 (−0.0295, 0.0573) |
| | 75–<115 | −0.1342 (−0.2596, −0.0088) [a] | −0.1332 (−0.2586, −0.0078)[a] | −0.1331 (−0.2584, −0.0077)[a] |
| | 115–<150 | −0.3167 (−0.634, 0.0007) [b] | −0.313 (−0.6304, 0.0044) [b] | −0.315 (−0.6322, 0.0023) [b] |
| | 150+ | −0.2698 (−0.9959, 0.4564) | −0.2715 (−0.9977, 0.4548) | −0.2667 (−0.9929, 0.4595) |
| Temperature (°C) | <0 (base) | | | |
| | 0–<7 | 0.0629 (−0.1583, 0.2842) | 0.0647 (−0.1565, 0.2859) | 0.0645 (−0.1567, 0.2857) |
| | 7–<12 | 0.1661 (−0.0629, 0.3952) | 0.1673 (−0.0617, 0.3963) | 0.1671 (−0.0618, 0.3961) |
| | 12–<18 | 0.1907 (−0.0405, 0.4219) | 0.1921 (−0.0391, 0.4232) | 0.1921 (−0.039, 0.4233) |
| | 18–<26 | 0.1705 (−0.0648, 0.4058) | 0.1724 (−0.0628, 0.4077) | 0.172 (−0.0632, 0.4072) |
| | 26+ | 0.1446 (−0.094, 0.3832) | 0.1462 (−0.0924, 0.3847) | 0.1454 (−0.0931, 0.384) |
| Rain | No (base) | | | |
| | Yes | 0.0221 (−0.0401, 0.0843) | 0.0225 (−0.0398, 0.0847) | 0.0225 (−0.0397, 0.0847) |
| Day | No (base) | | | |
| | Yes | 0.0375 (0.0042, 0.0708) [a] | 0.037 (0.0038, 0.0703) [a] | 0.0371 (0.0039, 0.0704) [a] |
| Day of week | Weekend (base) | | | |
| | Weekday | −0.0226 (−0.0573, 0.0121) | −0.0221 (−0.0569, 0.0126) | −0.022 (−0.0567, 0.0127) |

Note: [a] significant at $p$ of 0.05; [b] significant at $p$ of 0.1.

The variation in the performance of variables across different spatial scale models is also evident from the data presented in Table 1. The coefficients of GVI and public sentiment exhibit greater magnitudes than those of NDVI in each spatial scale model. The highest coefficient for GVI is observed in the 1000 m model, while the lowest is found in the 200 m model. Conversely, the highest coefficient for NDVI is identified in the 200 m model. At this particular scale (200 m), GVI and NDVI demonstrate similar coefficients with respect to public sentiment, albeit with slightly greater values for GVI. Notably, GVI and public sentiment exhibit significant positive correlations across all three models at scales of 200 m, 500 m, and 1000 m, yielding coefficients of 0.0053, 0.0116, and 0.0178 for public sentiment factors, respectively. Furthermore, as the spatial coverage range of GVI around check-in locations expands, the correlation coefficient gradually increases. However, only the 200 m scale exhibited a significant correlation with NDVI, with coefficients of 0.0044, 0.0015, and −0.0006 for public sentiment factors in the 200 m, 500 m, and 1000 m models, respectively. The NDVI and public sentiment coefficient gradually decrease with increasing spatial scale around the location. The characteristics of the other covariates in the 500 m and 1000 m models resemble those observed in the 200 m model.

### *3.3. Interaction between Greening Index and POI Type*

Figure 5 and Table A4 show the interaction results between the green land index and POI types. The research results confirm that GVI can generally better characterize the sentiment benefits of spatial green spaces for the public than can NDVI in various socioeconomic places. For every 0.01 increase in NDVI, the public sentiment coefficient shows a significant positive correlation only at the 200 m scale for public service areas; this correlation is not significant at other types and scales. Excluding industrial areas, in other types of locations, the public sentiment coefficient for GVI exhibits an upwards trend with the increase in scale. For instance, with each unit increase in GVI in residential areas, the corresponding coefficients at distances of 200 m, 500 m, and 1000 m are 0.0077, 0.0094, and 0.0143, respectively.

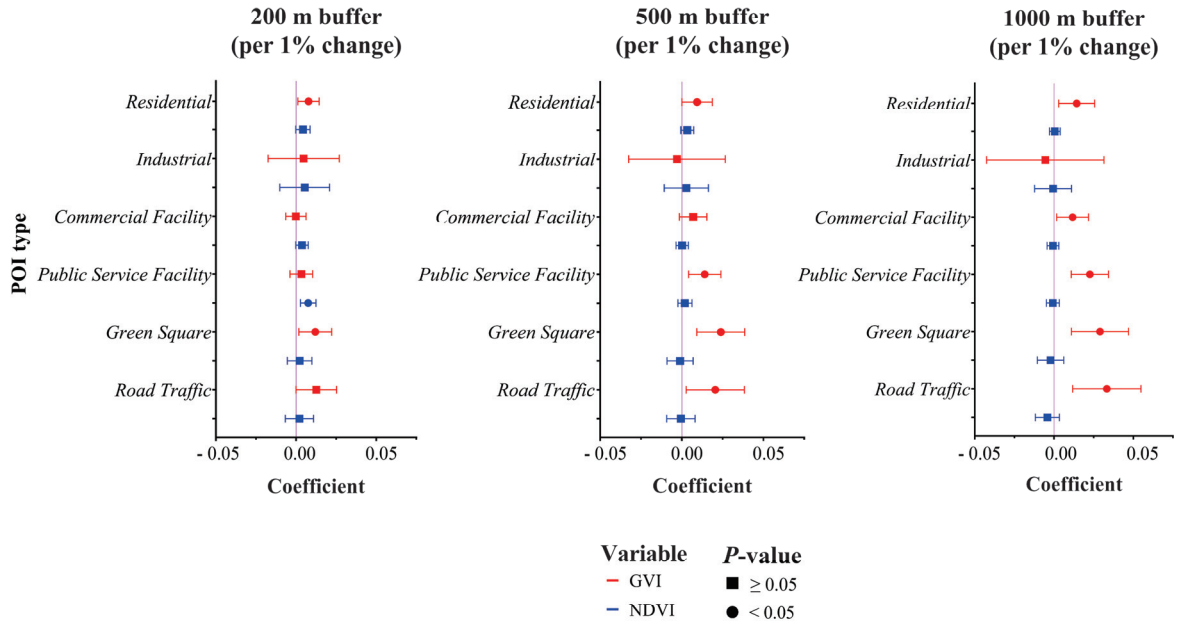



**Figure 5.** Forest plot of the interaction between POI type and greening index.

At the spatial scale of 200 m, the coefficients of the GVI and public sentiment are statistically significant only in residential and green park areas, with values of 0.0077 and 0.0126, respectively. At the larger 500 m scale, excluding residential and green spaces, the coefficients for GVI and public sentiment also show significance in relation to traffic and public service types, with values of 0.0205 and 0.0141, respectively. When considering a broader scale of 1000 m, a 1% increase in GVI has the greatest impact on public sentiment regarding road traffic, as indicated by a coefficient value of 0.0333. Furthermore, at this scale (1000 m), GVI can effectively reflect the association between green space availability and public sentiment across various socioeconomic categories; particularly notable improvements are exhibited for traffic-related places, while business-related places exhibit relatively minor enhancements.

## 4. Discussion

### *4.1. The Influence of GVI and NDVI on Sentiment*

Our research indicates that GVI is more suitable than NDVI as a greenness indicator for studying public sentiment represented by Weibo (Table 1; Figure 4). Based on quantitative comparisons of the correlations between GVI and public sentiment and NDVI and public sentiment, GVI is clearly a more suitable indicator for studying the relationship between human perception of greenness and public sentiment [49]. The deviation between NDVI and GVI becomes larger as the scale expands, but at smaller scales, the two may exhibit some degree of substitution. The occurrence of this phenomenon can be attributed to the frequent interaction between GVI and public activities, while NDVI exhibits significant disparities with areas of public activity. Another contributing factor is that GVI, as a three-dimensional indicator of green spaces, aligns more closely with human visual perception than does the NDVI, which represents green spaces two-dimensionally. Previous health studies based on GPS activities, scales, and physiological levels have also shown that GVI is superior to two-dimensional green space indicators. Our study further confirms this point from the perspective of social media data. From the perspective of the public's activity range and perspective, GVI has a relatively independent and irreplaceable influence on public sentiment, and it cannot be inferred simply from NDVI. The concept of "planning GVI" should be expeditiously disseminated, and GVI databases based on plant morphology, specifications, and age should be established for early prediction of future GVI in green space planning and construction [8].

Overall, a positive correlation exists between public sentiment and green spaces, which is consistent with the findings of previous research indicating that high-quality green spaces can enhance public sentiment [12,24,27–29,50]. As urban populations continue to grow, these findings highlight the potential importance of green spaces in promoting positive public sentiment. The effect sizes of our findings are relatively small, but these small effects could still have a positive impact. For urban populations, the small differences we found among the check-in locations could translate into larger differences across cities [12]. For example, when the population of Hangzhou exceeds the 10 million mark, for every 1% increase in the probability of positive sentiment of the urban population, the improvement of green space will improve the sentiment of approximately 100,000 people in the city. This is of great significance to the planning and management of urban green space.

### *4.2. Differences in Public Sentiment among Different Socioeconomic Location Types*

We confirmed the feasibility of capturing variations in public sentiment among different socioeconomic groups based on POI type (Table 1). Notably, comparative results across socioeconomic categories reveal lower levels of public sentiment in residential areas, potentially due to a relative lack of social support for residents who have been confined to their homes for extended periods. These residents are more susceptible to mental health issues, such as depression and loneliness [51], particularly among individuals with preexisting medical conditions [52]. Similarly, transportation categories also exhibit relatively low levels of public sentiment due to increased exposure to environmental factors such as air pollution [33,53], traffic noise [54], and traffic safety concerns [45]. Conversely, green parks demonstrate higher levels of public sentiment than other locations, followed by commercial areas. These types of places tend to facilitate leisure and entertainment activities, which generally contribute to elevated sentiments.

### *4.3. The impact of Green Space on Public Sentiment in Different Location Types*

The impact of green spaces on public sentiment varies across different socioeconomic settings. In this study, we primarily focus on comparing and discussing the influence of GVI changes (Figure 5). In contrast to Wei et al.'s [29] study, in which no correlation was found between public sentiment and residential green spaces based on microblog data, our findings indicate a positive correlation between the quality of surrounding green spaces and residential types at various buffer scales. These results align more closely with previous traditional research [34,42]. Residential areas characterized by abundant greenery are generally acknowledged to possess enhanced restorative qualities, heightened mindfulness, and greater stress resilience [34]. Moreover, the presence of natural spaces within communities may help alleviate social isolation [55] by fostering increased social support networks, thereby enhancing public sentiment in residential areas. Notably, the positive impact of green spaces on public sentiment at transportation sites is most pronounced when considering a scale of 1000 m due to the heightened exposure to green environments during public travel. Furthermore, higher levels and broader coverage of green spaces can mitigate adverse environmental exposures faced by the general population by reducing noise and particulate matter (PM) [43,56], consequently improving the overall sentiment. Due to differences in functionality, green park areas have varying effects [27]. Green parks of different sizes provide space for various activities for the majority of the public, and higher levels and wider coverage of green spaces promote sentiment for such activities more significantly. This finding is consistent with previous findings [32], which showed that happiness among visitors to 34 green parks in three northeastern provinces of China was significantly positively correlated with the green area and NDVI based on social media facial photo data. Lin et al. [12] also reported that the probability of negative expressions in large natural parks in Seattle was lower than that in other parks and nonpark areas.

Spatial and temporal variations in the relationship between sentiment and green spaces are indicated by different buffer zone correlations. Lin et al. [12] found a positive correlation between individuals' sentiment and tree canopy coverage in industrial zones

at a grid scale of 90 m, whereas our findings did not indicate such a relationship in work-related areas where people spend most of their time indoors at a single location. Our minimum range of 200 m differs significantly from the activity range of Lin et al., suggesting that green spaces may still have the potential to improve public sentiment in work areas. Lin et al. [12] also discovered that at a grid scale of 90 m, there is a tendency for individuals in commercial/mixed areas to exhibit negative sentiment given a higher degree of tree canopy. In contrast, our study reveals a positive correlation between public sentiment and green spaces in both commercial and public service areas at larger scales. The enhancement of urban green spaces can indeed enhance public sentiment; however, public sentiment is also influenced by the activity forms and spatiotemporal contexts of public groups. The variations observed across different spatial scales may reflect distinct modes of interaction between public group activities and green space. For instance, the large-scale environmental regulation and visual improvement of green spaces are more prominent, while vegetation contact at smaller scales can have adverse effects, such as by being common allergen sources [57] or exacerbating air pollution due to unreasonable vegetation layouts [58].

### *4.4. Green Space Optimization Based on the Psychological Benefits to Younger Populations*

By using the socioeconomic status of different check-in locations to examine the relationship between green spaces and public sentiment, this research is highly important for the sustainable development of cities, as mentioned in the introduction. Previous studies on green spaces and health have proposed improvement strategies for residential and park green spaces for vulnerable groups, such as elderly people and young children [20,21,59]. However, those in Chinese youth groups have limited sentiment benefits from residential and park green spaces due to their high work-life pressures [22]. Socioeconomic level differences are generally considered key to green space equity in terms of design availability [26]. However, due to the mismatch between the green space needs of youth groups and those of traditionally considered vulnerable groups, such as elderly people and young children, the ecosystem services that green spaces can provide remain unequal [40].

In particular, the separation of work and housing causes fixed daily commuting problems for Hangzhou's youth groups. Transportation stations, such as subways and buses, are important commuter access points, and the green spaces around these stations can provide daily green space [60]. The extensive high green spaces around transportation stations can complement their natural sentiment needs, restore attention [15], alleviate work-life pressures [14], and improve the sentiment of youth groups in their daily lives. In addition, youth groups have high visitation rates to commercial locations, such as shopping malls and food service venues. Improving the green spaces around these locations can facilitate the daily green space exposure of youth groups. Therefore, when using green spaces as health intervention measures to regulate public sentiment, the government can consider matching the needs of most youth groups for green spaces based on differences in public activity at different locations, such as promoting mixed land use to better utilize urban green space and breaking down as much as possible the boundaries between urban areas and parks and various types of green spaces. These techniques are conducive to urban equity and sustainable development strategies.

### *4.5. Limitations and Prospects*

Although our research confirms the differential impact of surrounding green spaces on public sentiment in different socioeconomic locations, there are limitations. First, the text sentiment expressed by Weibo users at geographic check-in points may not represent the expressions of the entire population at that location but only a portion of Weibo users [29]. Second, Weibo text is not a direct report of public sentiment. Sentiment expressed publicly on social media platforms may not truly reflect people's real sentiment states. Only a few Weibo posts are direct sentiment expressions, and achieving high accuracy with language interpretation tools is difficult [12]. Third, the activities and spatiotemporal contexts of

public sentiment expression at check-in points have significant uncertainty. Assessing to what extent the public has experienced green space before expressing sentiment at a location and in what form the activities were experienced is difficult. As a result, it is difficult for us to directly match green spaces with public sentiment expressions. Although the setting of surrounding buffer zones and data cleansing alleviate these impacts to some extent, the purely cross-sectional study design makes it difficult to make direct causal inferences and explore potential mechanisms. In the future, further research should combine traditional methods such as human sensors and questionnaire consultations to further clarify the differential perception of green surroundings by the public in different socioeconomic locations.

## 5. Conclusions

The benefits of promoting public sentiment through green spaces have always been highly valued, and new forms of social media data provide prospects for investigating the relationship between public sentiment and green spaces. This study reveals the impact of green environments around different socioeconomic locations on public sentiment. The research shows that (1) NDVI and GVI are positively correlated with public sentiment at 200 m scales, but only GVI enhancement can promote public sentiment at larger scales; (2) compared with other types, the public sentiment in residential areas is the lowest, while that in parks is the highest; (3) for young people, green space improvement at a 1000 m scale around traffic-related sites has the best effect. Therefore, based on our research, it is recommended that urban green space planning strengthen the improvement of green spaces around transportation-related locations. In addition, the relationship between urban green spaces and public sentiment is complex and subtle, and the way people engage in activities and their spatial and temporal contexts are also particularly important. Urban green space planning should also comprehensively consider various influencing factors.

**Author Contributions:** Conceptualization, L.L.; methodology, J.Z.; software, J.Z.; validation, Y.R.; formal analysis, T.J.; investigation, J.W.; resources, J.C.; data curation, L.L. and Y.R.; writing—original draft preparation, J.Z. and L.L.; writing—review and editing, J.Z. and L.L.; visualization, Y.R.; supervision, T.J.; project administration, D.D.; funding acquisition, J.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Forestry Science and Technology Cooperation Project between Zhejiang Province and the Chinese Academy of Forestry [grant numbers 2022SY04], the National Natural Science Foundation of China [grant numbers 32101573], the Natural Science Foundation of Zhejiang Province [grant numbers LQ20D050002], and the Research Development Foundation of Zhejiang A&F University [grant numbers 2018FR056].

**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Acknowledgments:** Authors acknowledge Xinhua Wang for assistance in data collection.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Appendix A

*Appendix A.1 Random Intercept Logistic Regression Model*

To demonstrate the relationship between the estimated coefficient and probabilities, we use a logistic regression model as a simple example. We know that for any logistic regression model, the formula is:

$$logit(p) = log(\frac{p}{1\quad p}) = \beta_0 + \beta_1 x_1 + \ldots + \beta_k x_k \quad \text{(A1)}$$

Note: $\beta_1$ is the coefficient of variable $x_1$, $\beta_k$ is the coefficient of variable $x_k$, and $\beta_0$ is the intercept.

For hierarchical data, high-level data corresponds to different data subsets. Only intercept is regarded as a random effect, and the variation of intercept is split. The random intercept model is as follows:

$$Y_{ij} = \beta_{0j} + \beta_1 x_{ij} + e_{0ij} = \beta_0 + u_{0j} + \beta_1 x_{ij} + e_{0ij} \quad \text{(A2)}$$

Note that $Y_{ij}$ is the measurement for the i subject at the j level. $x_{ij}$ covariates for the j level i subject. Where $(\beta_0 + \beta_1 x_{ij})$ is the fixed part, $(u_{0j} + e_{0ij})$ is the random intercept part.

Then, the random intercept ordered logistic regression model is as follows:

$$logit(p) = \beta_{0j} + \beta_1 x_1 + \ldots + \beta_k x_k + e_{0ij} \quad \text{(A3)}$$

**Table A1.** Mixed model and fixed model compares performance summary.

| Performance Statistic | 200 m | | 500 m | | 1000 m | |
|---|---|---|---|---|---|---|
| | Mixed Model | Fixed Model | Mixed Model | Fixed Model | Mixed Model | Fixed Model |
| AIC | 118,581.1 | 123,120.6 | 118,580.9 | 123,129.2 | 118,574.8 | 123,003.2 |
| | 0.033 | | 0.033 | | 0.032 | |

**Table A2.** Categorical variable summary.

| Categorical Variable | | Frequency | Percentage |
|---|---|---|---|
| Sentiment | Negative | 19,466 | 18.5 |
| | Neutral | 2657 | 2.53 |
| | Positive | 83,091 | 78.97 |
| POI type | Residential (base) | 25,843 | 24.56 |
| | Industrial | 2405 | 2.29 |
| | Commercial Facility | 32,874 | 31.24 |
| | Public Service Facility | 31,424 | 29.87 |
| | Green Square | 8541 | 8.12 |
| | Road Traffic | 4127 | 3.92 |
| Dew point (°C) | ≤2 (base) | 8020 | 7.62 |
| | 2–<16 | 34,307 | 32.61 |
| | 16+ | 62,887 | 59.77 |
| $PM_{2.5}$ (μg/m$^3$) | ≤35 (base) | 83,818 | 79.66 |
| | 35–<75 | 19,421 | 18.46 |
| | 75–<115 | 1706 | 1.62 |
| | 115–<150 | 222 | 0.21 |
| | 150+ | 47 | 0.04 |
| Temperature (°C) | <0 (base) | 583 | 0.55 |
| | 0–<7 | 6855 | 6.52 |
| | 7–<12 | 11,550 | 10.98 |
| | 12–<18 | 16,493 | 15.68 |
| | 18–<26 | 29,519 | 28.06 |
| | 26+ | 40,214 | 38.22 |
| Rain | No (base) | 97,696 | 92.85 |
| | Yes | 7518 | 7.15 |
| Day | No (base) | 57,906 | 55.04 |
| | Yes | 47,308 | 44.96 |
| Day of week | Weekend (base) | 32,798 | 31.17 |
| | Weekday | 72,416 | 68.83 |

**Table A3.** Continuous variable summary.

| Continuous Variable | Median (P25, P75) | IQR |
|---|---|---|
| Buffer of average GVI (%) | | |
| GVI 200 m | 11.22 (7.43, 15.54) | 8.11 |
| GVI 500 m | 11.44 (9.38, 15.39) | 6.01 |
| GVI 1000 m | 12.35 (10.35, 14.53) | 4.18 |
| Buffer of average NDVI (%) | | |
| NDVI 200 m | 12.18 (6.27, 20.04) | 13.77 |
| NDVI 500 m | 13.99 (8.72, 22.36) | 13.64 |
| NDVI 1000 m | 14.55 (9.30, 22.36) | 13.06 |

**Table A4.** Estimation results for the interaction between greening index and POI type.

| Buffer Size | POI Type | Coefficient (95% CI) | |
|---|---|---|---|
| | | GVI | NDVI |
| 200 m | Residential | 0.0077 (0.0011,0.0143) [a] | 0.0043 (−0.0002,0.0087) [b] |
| | Industrial | 0.0047 (−0.0175,0.0269) | 0.0054 (−0.0102,0.0209) |
| | Commercial Facility | −0.0001 (−0.0065,0.0062) | 0.0037 (−0.0002,0.0076) [b] |
| | Public Service Facility | 0.0032 (−0.0038,0.0103) | 0.0075 (0.0027,0.0124) [a] |
| | Green Square | 0.0119 (0.0017,0.0222) [a] | 0.0022 (−0.0055,0.0099) |
| | Road Traffic | 0.0126 (−0.0001,0.0252) [b] | 0.002 (−0.0068,0.0109) |
| 500 m | | | |
| | Residential | 0.0094 (0,0.0187) [a] | 0.0034 (−0.0006,0.0073) [b] |
| | Industrial | −0.0029 (−0.0325,0.0267) | 0.0028 (−0.0108,0.0164) |
| | Commercial Facility | 0.007 (−0.0015,0.0154) | 0.0003 (−0.0035,0.0041) |
| | Public Service Facility | 0.0141 (0.0042,0.0239) [a] | 0.0019 (−0.0023,0.0062) |
| | Green Square | 0.0239 (0.0093,0.0386) [a] | −0.0011 (−0.0091,0.0069) |
| | Road Traffic | 0.0205 (0.0027,0.0384) [a] | −0.0006 (−0.0093,0.0081) |
| 1000 m | | | |
| | Residential | 0.0143 (0.0029,0.0256) [a] | 0.0005 (−0.0029,0.0039) |
| | Industrial | 0.0055 (−0.0425,0.0315) | −0.0006 (−0.0123,0.011) |
| | Commercial Facility | 0.0117 (0.0016,0.0217) [a] | −0.0007 (−0.0044,0.003) |
| | Public Service Facility | 0.0226 (0.0108,0.0343) [a] | −0.0008 (−0.0048,0.0033) |
| | Green Square | 0.029 (0.011,0.0469) [a] | −0.0022 (−0.0105,0.0061) |
| | Road Traffic | 0.0333 (0.0117,0.0548) [a] | −0.0042 (−0.0118,0.0034) |

Note: [a] significant at $p$ of 0.05; [b] significant at $p$ of 0.1.

## References


1. Zhou, Y.; Varquez, A.C.G.; Kanda, M. High-Resolution Global Urban Growth Projection Based on Multiple Applications of the SLEUTH Urban Growth Model. *Sci. Data* **2019**, *6*, 34. [CrossRef] [PubMed]
2. He, C.; Liu, Z.; Tian, J.; Ma, Q. Urban Expansion Dynamics and Natural Habitat Loss in China: A Multiscale Landscape Perspective. *Glob. Change Biol.* **2014**, *20*, 2886–2902. [CrossRef] [PubMed]
3. Jamalishahni, T.; Turrell, G.; Foster, S.; Davern, M.; Villanueva, K. Neighbourhood Socio-Economic Disadvantage and Loneliness: The Contribution of Green Space Quantity and Quality. *BMC Public Health* **2023**, *23*, 598. [CrossRef]
4. Zhang, P.; Huang, N.; Yang, F.; Yan, W.; Zhang, B.; Liu, X.; Peng, K.; Guo, J. Determinants of Depressive Symptoms at Individual, School and Province Levels: A National Survey of 398,520 Chinese Children and Adolescents. *Public Health* **2024**, *229*, 33–41. [CrossRef] [PubMed]
5. McMahan, E.A.; Estes, D. The Effect of Contact with Natural Environments on Positive and Negative Affect: A Meta-Analysis. *J. Posit. Psychol.* **2015**, *10*, 507–519. [CrossRef]
6. Bratman, G.N.; Anderson, C.B.; Berman, M.G.; Cochran, B.; de Vries, S.; Flanders, J.; Folke, C.; Frumkin, H.; Gross, J.J.; Hartig, T.; et al. Nature and Mental Health: An Ecosystem Service Perspective. *Sci. Adv.* **2019**, *5*, eaax0903. [CrossRef] [PubMed]
7. Liu, Y.; Wang, R.; Grekousis, G.; Liu, Y.; Yuan, Y.; Li, Z. Neighbourhood Greenness and Mental Wellbeing in Guangzhou, China: What Are the Pathways? *Landsc. Urban Plan.* **2019**, *190*, 103602. [CrossRef]
8. Zhu, H.; Nan, X.; Yang, F.; Bao, Z. Utilizing the Green View Index to Improve the Urban Street Greenery Index System: A Statistical Study Using Road Patterns and Vegetation Structures as Entry Points. *Landsc. Urban Plan.* **2023**, *237*, 104780. [CrossRef]
9. Zhu, H.; Yang, F.; Bao, Z.; Nan, X. A Study on the Impact of Visible Green Index and Vegetation Structures on Brain Wave Change in Residential Landscape. *Urban For. Urban Green.* **2021**, *64*, 127299. [CrossRef]
10. Wang, R.; Yang, B.; Yao, Y.; Bloom, M.S.; Feng, Z.; Yuan, Y.; Zhang, J.; Liu, P.; Wu, W.; Lu, Y.; et al. Residential Greenness, Air Pollution and Psychological Well-Being among Urban Residents in Guangzhou, China. *Sci. Total Environ.* **2020**, *711*, 134843. [CrossRef]
11. Duan, S.; Shen, Z.; Luo, X. Exploring the Relationship between Urban Youth Sentiment and the Built Environment Using Machine Learning and Weibo Comments. *Int. J. Environ. Res. Public Health* **2022**, *19*, 4794. [CrossRef] [PubMed]
12. Lin, Y.; Wood, S.A.; Lawler, J.J. The Relationship between Natural Environments and Subjective Well-Being as Measured by Sentiment Expressed on Twitter. *Landsc. Urban Plan.* **2022**, *227*, 104539. [CrossRef]
13. Hirons, M.; Comberti, C.; Dunford, R. Valuing Cultural Ecosystem Services. *Annu. Rev. Environ. Resour.* **2016**, *41*, 545–574. [CrossRef]
14. Ulrich, R.S.; Simons, R.F.; Losito, B.D.; Fiorito, E.; Miles, M.A.; Zelson, M. Stress Recovery during Exposure to Natural and Urban Environments. *J. Environ. Psychol.* **1991**, *11*, 201–230. [CrossRef]
15. Kaplan, S. The Restorative Benefits of Nature: Toward an Integrative Framework. *J. Environ. Psychol.* **1995**, *15*, 169–182. [CrossRef]
16. Gladwell, V.F.; Brown, D.K.; Wood, C.; Sandercock, G.R.; Barton, J.L. The Great Outdoors: How a Green Exercise Environment Can Benefit All. *Extrem. Physiol. Med.* **2013**, *2*, 3. [CrossRef] [PubMed]

17. Maas, J.; Van Dillen, S.M.E.; Verheij, R.A.; Groenewegen, P.P. Social Contacts as a Possible Mechanism behind the Relation between Green Space and Health. *Health Place* **2009**, *15*, 586–595. [CrossRef]
18. Dadvand, P.; de Nazelle, A.; Triguero-Mas, M.; Schembari, A.; Cirach, M.; Amoly, E.; Figueras, F.; Basagaña, X.; Ostro, B.; Nieuwenhuijsen, M. Surrounding Greenness and Exposure to Air Pollution During Pregnancy: An Analysis of Personal Monitoring Data. *Environ. Health Perspect.* **2012**, *120*, 1286–1290. [CrossRef]
19. Nesbitt, L.; Meitner, M.J.; Girling, C.; Sheppard, S.R.J.; Lu, Y. Who Has Access to Urban Vegetation? A Spatial Analysis of Distributional Green Equity in 10 US Cities. *Landsc. Urban Plan.* **2019**, *181*, 51–79. [CrossRef]
20. Fernandes, A.; Krog, N.H.; McEachan, R.; Nieuwenhuijsen, M.; Julvez, J.; Márquez, S.; De Castro, M.; Urquiza, J.; Heude, B.; Vafeiadi, M.; et al. Availability, Accessibility, and Use of Green Spaces and Cognitive Development in Primary School Children. *Environ. Pollut.* **2023**, *334*, 122143. [CrossRef]
21. Xu, T.; Nordin, N.A.; Aini, A.M. Urban Green Space and Subjective Well-Being of Older People: A Systematic Literature Review. *Int. J. Environ. Res. Public Health* **2022**, *19*, 14227. [CrossRef] [PubMed]
22. Zhang, F.; Xu, W.; Khurshid, A. The Interplay of Migrant Workers' Working Hours, Income, and Well-Being in China. *Sustainability* **2023**, *15*, 11409. [CrossRef]
23. Alves, L.; Silva, S.; Severo, M.; Costa, D.; Pina, M.F.; Barros, H.; Azevedo, A. Association between Neighborhood Deprivation and Fruits and Vegetables Consumption and Leisure-Time Physical Activity: A Cross-Sectional Multilevel Analysis. *BMC Public Health* **2013**, *13*, 1103. [CrossRef] [PubMed]
24. Brindley, P.; Cameron, R.W.; Ersoy, E.; Jorgensen, A.; Maheswaran, R. Is More Always Better? Exploring Field Survey and Social Media Indicators of Quality of Urban Greenspace, in Relation to Health. *Urban For. Urban Green.* **2019**, *39*, 45–54. [CrossRef]
25. Kovacs-Györi, A.; Ristea, A.; Kolcsar, R.; Resch, B.; Crivellari, A.; Blaschke, T. Beyond Spatial Proximity—Classifying Parks and Their Visitors in London Based on Spatiotemporal and Sentiment Analysis of Twitter Data. *ISPRS Int. J. Geo-Inf.* **2018**, *7*, 378. [CrossRef]
26. Lusseau, D.; Baillie, R. Disparities in Greenspace Access during COVID-19 Mobility Restrictions. *Environ. Res.* **2023**, *225*, 115551. [CrossRef]
27. Kong, L.; Liu, Z.; Pan, X.; Wang, Y.; Guo, X.; Wu, J. How Do Different Types and Landscape Attributes of Urban Parks Affect Visitors' Positive Emotions? *Landsc. Urban Plan.* **2022**, *226*, 104482. [CrossRef]
28. Plunz, R.A.; Zhou, Y.; Carrasco Vintimilla, M.I.; Mckeown, K.; Yu, T.; Uguccioni, L.; Sutto, M.P. Twitter Sentiment in New York City Parks as Measure of Well-Being. *Landsc. Urban Plan.* **2019**, *189*, 235–246. [CrossRef]
29. Sun, P.; Lu, W.; Jin, L. How the Natural Environment in Downtown Neighborhood Affects Physical Activity and Sentiment: Using Social Media Data and Machine Learning. *Health Place* **2023**, *79*, 102968. [CrossRef]
30. De Vries, S.; Nieuwenhuizen, W.; Farjon, H.; Van Hinsberg, A.; Dirkx, J. In Which Natural Environments Are People Happiest? Large-Scale Experience Sampling in the Netherlands. *Landsc. Urban Plan.* **2021**, *205*, 103972. [CrossRef]
31. Zhu, C.; Zhang, X.; Zhou, M.; He, S.; Gan, M.; Yang, L.; Wang, K. Impacts of Urbanization and Landscape Pattern on Habitat Quality Using OLS and GWR Models in Hangzhou, China. *Ecol. Indic.* **2020**, *117*, 106654. [CrossRef]
32. Zhu, X.; Gao, M.; Zhang, R.; Zhang, B. Quantifying Emotional Differences in Urban Green Spaces Extracted from Photos on Social Networking Sites: A Study of 34 Parks in Three Cities in Northern China. *Urban For. Urban Green.* **2021**, *62*, 127133. [CrossRef]
33. Zheng, S.; Wang, J.; Sun, C.; Zhang, X.; Kahn, M.E. Air Pollution Lowers Chinese Urbanites' Expressed Happiness on Social Media. *Nat. Hum. Behav.* **2019**, *3*, 237–243. [CrossRef]
34. Dzhambov, A.M.; Hartig, T.; Tilov, B.; Atanasova, V.; Makakova, D.R.; Dimitrova, D.D. Residential Greenspace Is Associated with Mental Health via Intertwined Capacity-Building and Capacity-Restoring Pathways. *Environ. Res.* **2019**, *178*, 108708. [CrossRef]
35. Yao, Y.; Liang, Z.; Yuan, Z.; Liu, P.; Bie, Y.; Zhang, J.; Wang, R.; Wang, J.; Guan, Q. A Human-Machine Adversarial Scoring Framework for Urban Perception Assessment Using Street-View Images. *Int. J. Geogr. Inf. Sci.* **2019**, *33*, 2363–2384. [CrossRef]
36. Cheng, Y.; Yu, Z.; Xu, C.; Manoli, G.; Ren, X.; Zhang, J.; Liu, Y.; Yin, R.; Zhao, B.; Vejre, H. Climatic and Economic Background Determine the Disparities in Urbanites' Expressed Happiness during the Summer Heat. *Environ. Sci. Technol.* **2023**, *57*, 10951–10961. [CrossRef]
37. Du, S.; Zhang, F.; Zhang, X. Semantic Classification of Urban Buildings Combining VHR Image and GIS Data: An Improved Random Forest Approach. *ISPRS J. Photogramm. Remote Sens.* **2015**, *105*, 107–119. [CrossRef]
38. Liu, X.; He, J.; Yao, Y.; Zhang, J.; Liang, H.; Wang, H.; Hong, Y. Classifying Urban Land Use by Integrating Remote Sensing and Social Media Data. *Int. J. Geogr. Inf. Sci.* **2017**, *31*, 1675–1696. [CrossRef]
39. Miao, R.; Wang, Y.; Li, S. Analyzing Urban Spatial Patterns and Functional Zones Using Sina Weibo POI Data: A Case Study of Beijing. *Sustainability* **2021**, *13*, 647. [CrossRef]
40. Chen, Y.; Yang, J.; Yang, R.; Xiao, X.; Xia, J. Contribution of Urban Functional Zones to the Spatial Distribution of Urban Thermal Environment. *Build. Environ.* **2022**, *216*, 109000. [CrossRef]
41. Qiao, Y.; Labi, S.; Fricker, J.D. Does Highway Project Bundling Policy Affect Bidding Competition? Insights from a Mixed Ordinal Logistic Model. *Transp. Res. Part Policy Pract.* **2021**, *145*, 228–242. [CrossRef]
42. Mannering, F.L.; Bhat, C.R. Analytic Methods in Accident Research: Methodological Frontier and Future Directions. *Anal. Methods Accid. Res.* **2014**, *1*, 1–22. [CrossRef]
43. Helbich, M. Spatiotemporal Contextual Uncertainties in Green Space Exposure Measures: Exploring a Time Series of the Normalized Difference Vegetation Indices. *Int. J. Environ. Res. Public Health* **2019**, *16*, 852. [CrossRef] [PubMed]

44. Crouse, D.L.; Pinault, L.; Christidis, T.; Lavigne, E.; Thomson, E.M.; Villeneuve, P.J. Residential Greenness and Indicators of Stress and Mental Well-Being in a Canadian National-Level Survey. *Environ. Res.* **2021**, *192*, 110267. [CrossRef] [PubMed]
45. Klompmaker, J.O.; Hoek, G.; Bloemsma, L.D.; Wijga, A.H.; Van Den Brink, C.; Brunekreef, B.; Lebret, E.; Gehring, U.; Janssen, N.A.H. Associations of Combined Exposures to Surrounding Green, Air Pollution and Traffic Noise on Mental Health. *Environ. Int.* **2019**, *129*, 525–537. [CrossRef]
46. Li, F.; Yao, N.; Liu, D.; Liu, W.; Sun, Y.; Cheng, W.; Li, X.; Wang, X.; Zhao, Y. Explore the Recreational Service of Large Urban Parks and Its Influential Factors in City Clusters—Experiments from 11 Cities in the Beijing-Tianjin-Hebei Region. *J. Clean. Prod.* **2021**, *314*, 128261. [CrossRef]
47. Wang, R.; Browning, M.H.E.M.; Kee, F.; Hunter, R.F. Exploring Mechanistic Pathways Linking Urban Green and Blue Space to Mental Wellbeing before and after Urban Regeneration of a Greenway: Evidence from the Connswater Community Greenway, Belfast, UK. *Landsc. Urban Plan.* **2023**, *235*, 104739. [CrossRef]
48. Yang, H.; Wen, J.; Lu, Y.; Peng, Q. A Quasi-Experimental Study on the Impact of Park Accessibility on the Mental Health of Undergraduate Students. *Urban For. Urban Green.* **2023**, *86*, 127979. [CrossRef]
49. Ki, D.; Lee, S. Analyzing the Effects of Green View Index of Neighborhood Streets on Walking Time Using Google Street View and Deep Learning. *Landsc. Urban Plan.* **2021**, *205*, 103920. [CrossRef]
50. Yang, B.; Ta, W.; Dong, W.; Ma, D.; Duan, J.; Lin, H.; Dong, D.; Chen, J.; Zeng, S.; Shi, Y.; et al. Quantifying the Threshold Effects and Factors Impacting Physiological Health Benefits of Forest Exposure. *Forests* **2024**, *15*, 555. [CrossRef]
51. Costa-Cordella, S.; Vivanco-Carlevari, A.; Rossi, A.; Arévalo-Romero, C.; Silva, J.R. Social Support and Depressive Symptoms in the Context of COVID-19 Lockdown: The Moderating Role of Attachment Styles. *Int. J. Public Health* **2022**, *67*, 1604401. [CrossRef]
52. Zhang, Y.; Chen, Y.; Ma, L. Depression and Cardiovascular Disease in Elderly: Current Understanding. *J. Clin. Neurosci.* **2018**, *47*, 1–5. [CrossRef] [PubMed]
53. Hao, G.; Zuo, L.; Xiong, P.; Chen, L.; Liang, X.; Jing, C. Associations of PM2.5 and Road Traffic Noise with Mental Health: Evidence from UK Biobank. *Environ. Res.* **2022**, *207*, 112221. [CrossRef]
54. Okokon, E.O.; Yli-Tuomi, T.; Turunen, A.W.; Tiittanen, P.; Juutilainen, J.; Lanki, T. Traffic Noise, Noise Annoyance and Psychotropic Medication Use. *Environ. Int.* **2018**, *119*, 287–294. [CrossRef] [PubMed]
55. Rugel, E.J.; Carpiano, R.M.; Henderson, S.B.; Brauer, M. Exposure to Natural Space, Sense of Community Belonging, and Adverse Mental Health Outcomes across an Urban Region. *Environ. Res.* **2019**, *171*, 365–377. [CrossRef] [PubMed]
56. Zhang, X.; Wei, F.; Yu, Z.; Guo, F.; Wang, J.; Jin, M.; Shui, L.; Lin, H.; Tang, M.; Chen, K. Association of Residential Greenness and Incident Depression: Investigating the Mediation and Interaction Effects of Particulate Matter. *Sci. Total Environ.* **2022**, *811*, 152372. [CrossRef]
57. Aerts, R.; Stas, M.; Vanlessen, N.; Hendrickx, M.; Bruffaerts, N.; Hoebeke, L.; Dendoncker, N.; Dujardin, S.; Saenen, N.D.; Van Nieuwenhuyse, A.; et al. Residential Green Space and Seasonal Distress in a Cohort of Tree Pollen Allergy Patients. *Int. J. Hyg. Environ. Health* **2020**, *223*, 71–79. [CrossRef]
58. Yan, J.; Chen, W.Y.; Zhang, Z.; Zhao, W.; Liu, M.; Yin, S. Mitigating PM2.5 Exposure with Vegetation Barrier and Building Designs in Urban Open-Road Environments Based on Numerical Simulations. *Landsc. Urban Plan.* **2024**, *241*, 104918. [CrossRef]
59. Hao, N.; Li, X.; Han, D.; Nie, W. Quantifying the Impact of Street Greening during Full-Leaf Seasons on Emotional Perception: Guidelines for Resident Well-Being. *Forests.* **2024**, *15*, 119. [CrossRef]
60. Zhu, H.; Nan, X.; Kang, N.; Li, S. How Much Visual Greenery Can Street Trees Generate from a Humanistic Perspective? An Attempt to Quantify the Canopy Green View Index Based on Tree Morphology. *Forests* **2024**, *15*, 88. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# An Assessment of Accessibility from a Socially Sustainable Urban Mobility Approach in Mass Transit Projects: Contributions from the Northern Central American Triangle

**Carlos Ernesto Grande-Ayala** [1,2]

[1] Loyola Andalucía on Inclusive and Social Development Program, 14004 Córdoba, Spain; cgrande@uca.edu.sv
[2] Department of Spatial Organization, Universidad Centroamericana José Simeón Cañas, Antiguo Cuscatlán 01501, El Salvador

**Abstract:** This article aims to address the lack of research on the social dimension of sustainability, also known as social sustainability, in urban mobility projects, primarily in cities of the Global South. It proposes a strategy to partially assess social sustainability, focusing on accessibility, which is one of the key dimensions for conducting such an evaluation. To this end, a comparative analysis of three study cases is conducted in the capital cities of the Northern Central American Triangle (NCAT) before and after the construction of bus rapid transit (BRT) projects between 2000 and 2020. Accessibility is evaluated through equity and spatial efficiency indicators obtained through geographical information system (GIS) modeling, including layers representing transportation networks, populated areas, and locations of basic urban facilities. The result is an unprecedented assessment of accessibility in the NCAT capitals, which shows how the Guatemala City BRT project has improved the city's social sustainability by reducing access times to basic urban facilities, mainly public health clinics and educational facilities, and narrowing the inequality gap as compared to projects in San Salvador and Tegucigalpa, the other capital cities in the NCAT. Additionally, it is emphasized that this methodology can be replicated in the Global South while considering the scarcity of information and the use of open-source software in the process.

**Keywords:** urban planning; accessibility; BRT; equity; global south

**Citation:** Grande-Ayala, C.E. An Assessment of Accessibility from a Socially Sustainable Urban Mobility Approach in Mass Transit Projects: Contributions from the Northern Central American Triangle. *Sustainability* **2024**, *16*, 3766. https://doi.org/10.3390/su16093766

Academic Editors: Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Baojie He and Shi Cheng

Received: 18 January 2024
Revised: 15 March 2024
Accepted: 19 April 2024
Published: 30 April 2024

**Copyright:** © 2024 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Divergent assessments of sustainable development have been noted by scholars [1–4]. Dimitriou [5] emphasizes that sustainability in the field of transport can be perceived as a neo-imperialist notion that neglects local values. Urban mobility schemes in the Global South often overlook the social component of sustainability, implicitly assuming accessibility, inclusion, and equity in all transport services. To address this issue, Dimitriou suggests incorporating context-sensitive sustainable transport strategies.

The ideas about sustainable development that guide urban mobility projects and policies often end up excluding vulnerable social groups, leading to enormous expenses on projects that do not function properly and leaving a gap in efforts to improve the quality of life in more sustainable cities. On this matter, Dimitriou suggests incorporating sustainable transport strategies that are more sensitive to the specific context of each location.

This article proposes the Socially Sustainable Urban Mobility (SSUM) approach as an alternative to make sustainability context-sensitive, specifically in the Global South. The article analyzes three urban mobility modernization projects in the Northern Central American Triangle (NCAT) that were developed in the early 2000s and based on bus rapid transit (BRT) systems.

Although studies had been performed in the three countries of Guatemala, Honduras, and El Salvador pointing out the need to transform their mass transportation systems [6–8], the three initiatives gained momentum after being electoral promises made by mayoral candidates in the cases of Guatemala City and Tegucigalpa and by the central government in the case of San Salvador. This is not uncommon in the realm of transportation projects, as there is evidence that transportation initiatives can be influenced by partisan political considerations, an aspect that Flyvbjerg [9] defines as one of the four "sublimes" that together explain the magnitude of and increase in these projects.

Latin America has the highest number of BRT users worldwide, accounting for 59.5% [10]. However, the increase in private vehicles shown in Figure 1 highlights the unsustainability of urban mobility in the NCAT, which poses significant challenges. It is worth noting that the marked increase in motorbike use is contributing to a 44% rise in road crash fatality rates in low- and middle-income countries, as reported by Neki et al. [11]).

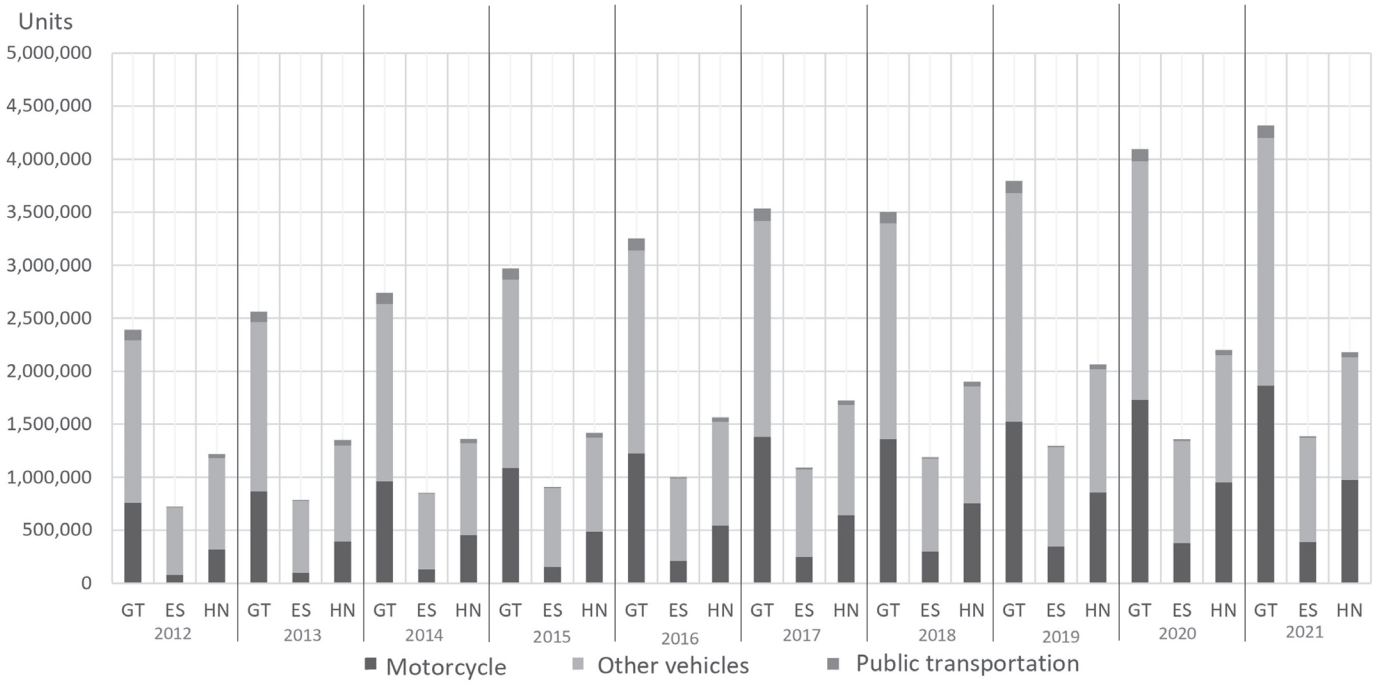



**Figure 1.** A decade of evolution in transportation modes in the NCAT. Source: Own elaboration based on [12–14]. Note: GT = Guatemala; ES = El Salvador; HN = Honduras.

However, public transportation persists as the primary mode of mobility in the three countries of the NCAT, with the utilization rates reaching 70% in San Salvador and Guatemala and approximately 60% in Honduras [8,15,16]. It is imperative to emphasize, nonetheless, that during the data collection for this research, a notable deficiency in measuring non-motorized travel and its proportion in daily journeys was evident. This lack of information highlights a substantial obstacle for conducting a meticulous assessment of the contribution of non-motorized travel to the public transportation system.

Therefore, this article contributes to the academic discourse in two ways. Firstly, it presents evidence on the social dimension of sustainability by assessing accessibility in an understudied region and in a widely used mode of transport. Additionally, it provides a methodological approach to assessing SSUM in urban mobility projects in urban areas of the Global South, using the NCAT countries as a case study. This article, which focuses on accessibility, is part of a broader research project examining SSUM in three critical categories, namely accessibility, community sustainability, and institutionality as shown in Figure 2.

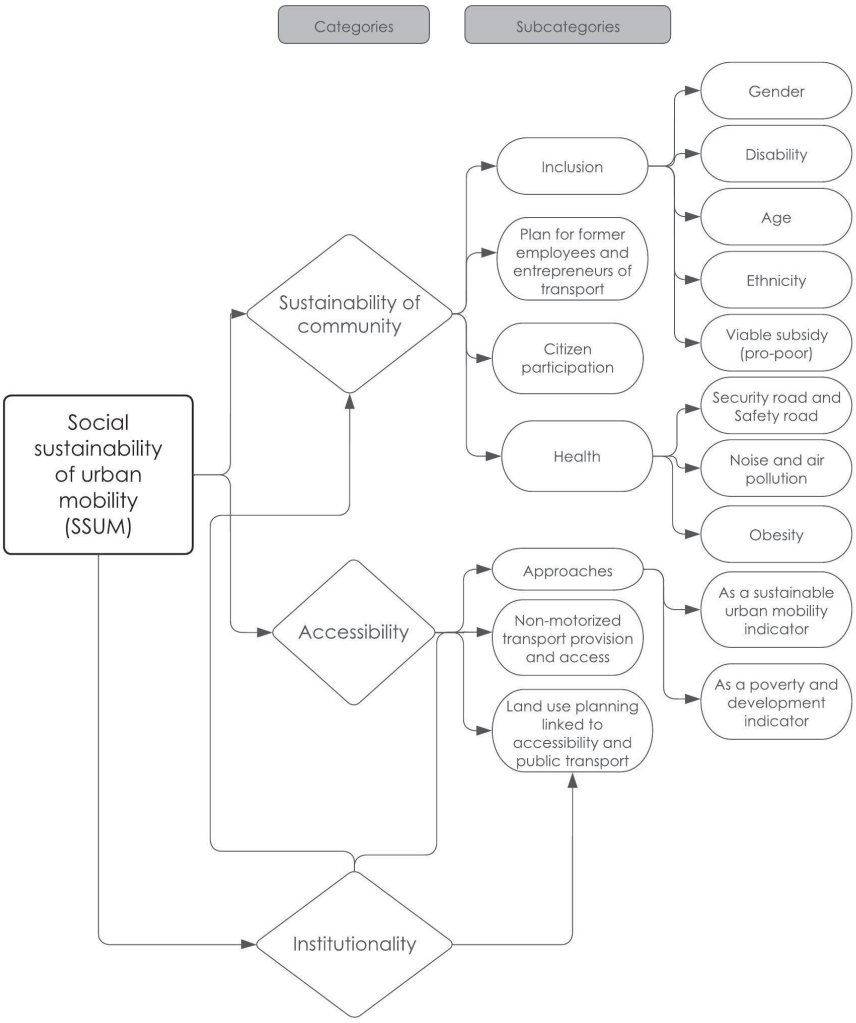



**Figure 2.** Synthesis of the conceptual framework for social sustainability in urban mobility. Source: Own elaboration based on [17].

*Socially Sustainable Urban Mobility as an Analytical Focus in the NCAT*

In relation to the SSUM approach in the NCAT, the contributions of Shirazi [3] are relevant when warning of the lack of academic attention to the social dimension of sustainable development theorization, evidencing its ambiguity, limited focus on developed countries, and predominant use in public policymaking. On this issue, Lineburg [17] demonstrates that the academic discourse on sustainability and transport tends to prioritize economic and environmental aspects, often relegating social considerations.

Despite these assertions, Vallance et al. [18] argue that there is a multiplicity of perspectives and contributions that help to define social sustainability, highlighting the urban planning approach [19], which suggests that to promote the social dimension of sustainable development it is essential to ensure equity and inclusion in urban transformation projects.

These principles on social sustainability in urban mobility research are recurrent and fundamental to understanding how transport projects can affect the social dimension of sustainable development. This article proposes four relevant conceptualizations of social sustainability to enrich the urban planning theory from the perspective of urban mobility systems and to provide continuity to the scholarly discussion on the importance of the aforementioned principles of equity and inclusion in social sustainability assessments. Lineburg [17] provides the structure shown in Figure 2, based on the concepts of community sustainability and accessibility, which have also been identified by other authors [20] as indicators for equity and inclusion assessment. Flora [21] and Cervero [22] provide useful resources for a thorough understanding of the implications of equity

(horizontal and vertical [23]) and inclusion in transport, which can help in understanding the social dimension from the perspective of the Global South, as well as the research by Pitarch-Garrido [24], which is methodologically relevant to this article.

Furthermore, Flora and Cervero [21,22] emphasize the importance of accessibility as an evaluation category in the SSUM, highlighting it as an indicator that helps to meet the requirement of measuring equitable access to urban amenities and employment, mainly through non-motorized mobility modes and land use planning in conjunction with public transport.

Additionally, this article supports the ideas of several authors [25–28], who argue that in the context of Global South countries, it is essential to incorporate a third category in the SSUM related to the inclusion of the political and institutional dimensions in order to achieve equitable mobility and build sustainable communities.

With these elements described in Figure 2 and mentioned above, it is possible to state that urban mobility will be socially sustainable when the benefits it generates in the city, namely the improvements in accessibility and community sustainability, are equitably and impartially distributed among the population, due to the participatory management of the leading institutions of the sociotechnical system of urban mobility, composed of transportation, land use and stakeholders.

However, this article focuses exclusively on an accessibility assessment as a category of SSUM and poses a specific research question: "From a SSUM approach, how can the assessment of accessibility be employed to measure progress in the social dimension of sustainable development in urban mobility projects in the capitals of the NCAT?"

This reasoning led to the formulation of the hypothesis, which suggests that in the Northern Central American Triangle, urban mobility interventions that incorporate aspects of social sustainability as a structuring focus contribute more significantly to the transformation of a city's exclusionary social structures than those that do not consider these aspects.

The next section justifies the selection of study cases, outlines the characteristics of the BRT projects and cities studied, details data management and quality processes, explains the research techniques and indicator selection, and discusses the impacts of these elements on the obtained results.

## 2. Materials and Methods

The research methodology aligns with the research question by selecting accessibility indicators linked to social sustainability. In line with Pitarch-Garrido's proposal [24], this study employed the concept of spatial equity to examine how the allocation of economic resources for a mass transit project has altered the population's access to educational, healthcare, recreational, and essential supplies located in urban facilities.

Spatial equity is a key indicator in assessing accessibility from the perspective of SSUM and can be defined as the ability to "meet local needs through efficient resource allocation to promote positive effects in space and overcome challenges related to the physical and social environment" [29]. It is important to note that the analysis of accessibility to urban services should also consider the levels of service provided and satisfaction, with an emphasis on sectors of the population that do not benefit from urban mobility. This article addresses this issue further in the discussion section.

From the vantage point of urban planning, this paper introduces an alternative methodology grounded in the use of open-access tools. It provides a comparative analysis of three BRT projects, evaluating their impacts on the overall quality of life. This evaluation integrates statistical and cartographic indicators. Notably, the research accentuates a SSUM approach, encompassing considerations such as the role of accessibility in fostering sustainable communities and its interconnectedness with social equity. It is pertinent to acknowledge that due to the scope of this article, the relevance of the institutional domain remains unexplored.

The selection of the study cases involving the three capital cities from the Northern Central American Triangle region was based on the significant number of commonalities between them. These include the implementation of BRT systems for mass transport, their

significant urban growth between 1990 and 2014, and the fact that they are conurbations and that have similar percentages of population in relation to the country as a whole (around 30%), among other aspects highlighted by Maria et al. [30], suggesting a certain degree of homogeneity among the selected cities.

However, despite these similarities, it is important to note that the three cities have achieved very different outcomes in their urban mobility projects. These differences present a unique opportunity to conduct comparative case studies and derive relevant interpretations. Moreover, these characteristics add interest to the comparative evaluation of ex ante and ex post BRT projects in NCAT countries and bridge the information gap on accessibility in that region, providing a valuable example of "maximum variation" [31], allowing for the evaluation of urban mobility projects in similar contexts but with different results.

The temporal threshold selected was between 2000 and 2020, during the planning and implementation of BRT projects, focusing solely on the limits of the NCAT capital cities, the border lines of which have been depicted in red in Figure 3.

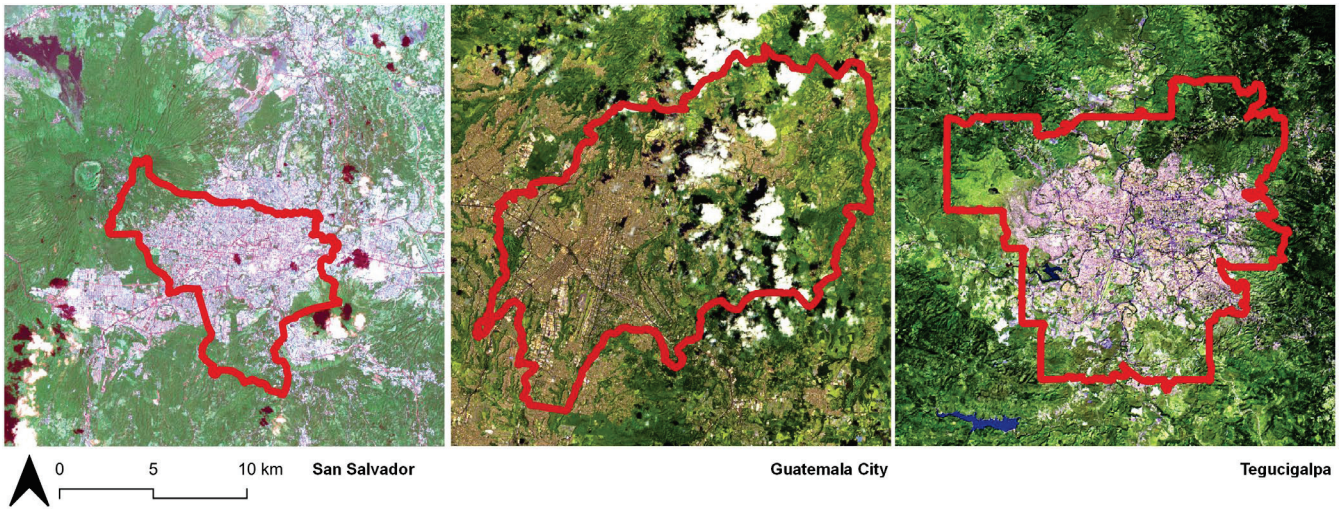



**Figure 3.** Urban growth of metropolitan areas in the NCAT. Source: Author's elaboration based on Sentinel 2 satellite images.

The description of the metropolitan areas can be brief, as those of the three NCAT capital city's house almost 9.9 million people. However, the capitals alone have a combined population of 2.78 million [32]. The three BRT systems of the NCAT capital cities have had diverse outcomes. Guatemala's TRANSMETRO remains operational, serving 210,000 daily passengers (approximately 17% of their population) across seven lines spanning 60 km. In contrast, San Salvador closed its 6 km BRT system in 2020, which had catered to 27,000 daily passengers (approximately 8% of their population). Although Tegucigalpa constructed a significant portion of infrastructure over a distance of 10 km, the project was never operationalized.

As outlined in the Introduction, accessibility is essential in an analysis of social sustainability. The concepts of accessibility can take various approaches, traditionally linked to disciplines such as urban economics, human geography, and city planning. In the former, as asserted by Goodall [33] and Camagni [34], accessibility is understood as a category that enables decision-making in the selection of business and residential locations to reduce travel costs within the city. Human geography emphasizes the accessibility levels of social groups, their locations, and the different levels of exclusion that are generated or perceived [35].

Methodologically, accessibility is used as an indicator for different purposes in different disciplines. In urban planning, Zegras [4] defines it as a robust indicator of sustainable urban mobility, which depending on the methodology can efficiently integrate the various components that shape its evaluation. The concept of accessibility is defined by Geurs and Van Wee [36] "as the extent to which land use and transport systems enable (groups of) individuals

to reach activities or destinations by means of a (combination of) transport mode(s)". This concept was adopted in this research for its comprehensiveness and the usefulness of its four evaluation perspectives. This study adopted the location-based evaluation perspective, as advocated by Zegras [4], which is capable of delineating spatial groupings in strata and population segments under conditions of exclusion, justifying its selection.

Hansen's [37] potential accessibility approach is widely used in urban planning as a measure of accessibility, as it assesses the inequality of opportunities in a territory due to origin, the locations of available services, distances, and the means of transport to access them. Since its creation, adjustments have been made to refine this measure, although the lack of empirical data on the attractiveness of trips to urban facilities (3590 in Table 1) in the capitals of the NCAT hinders its usefulness.

Given the availability of data, the alternative proposed by Moreno [38], which uses optimal location models (OLMs), has many advantages. OLMs have various applications, including the ability to establish a network of services and facilities and evaluate spatial schemes of current endowments, so our comparative evaluation used this process to focus on accessibility as an indicator of the SSUM.

Our optimal location model (OLM) [38] operationalized a location-based accessibility evaluation, using a 15 min tolerance parameter to identify levels of population exclusion and territorial inequalities before and after BRT projects. This study employed open-source software such as QGIS 3.32.0 and Flowmap 7.4 [39] to ensure process replication in resource-constrained contexts and to meet scientific requirements. QGIS was used to present the results, while Flowmap is used for impedance calculations and accessibility assessments.

The collected data were diverse, as there is no standardized data infrastructure (IDE) in Central America to facilitate the harmonization and exchange of information, similar to the INSPIRE initiative in Europe [40]. The selection process was complex not only due to the variety of information but also because the data originate from different institutions and countries following different standards of capture and indexing. Therefore, the data selection criterion was based on ensuring that the selected layers enabled the construction of a model that allowed a comparison between cities and included aspects such as census tracts, public transportation routes, road infrastructure, and the locations of basic urban amenities. Once the information was identified, the datasets displayed in Table 1 were selected.

The collected data required careful cleaning due to limitations in the bus stop locations and route frequency rates, resulting in a loss of precision in the network impedance calculation. The diversity of sources demanded meticulous homogenization of the information to generate territorial models (see Figure 4). The capacity of each facility was verified, and the existence of public spaces and public health clinics was validated through municipal portals and health ministries for all countries. Private educational institutions were also included, taking into account the approximately 50% public–private distribution in the three countries [12,41], as well as markets and supply centers.

The territorial models developed for each of the NCAT capital cities included the intermodal road network, which comprises pedestrian, conventional bus, and BRT systems. The road network topology was adjusted, and routes and commercial speeds for conventional buses, BRT, and pedestrians were examined.

The territorial model can be characterized as static in terms of demographics and infrastructure. In this sense, these variables remain constant and provide a snapshot at a specific point in time, offering a basic understanding of the state in which the model was developed in 2021. However, this highlights its ability to describe the impacts of the BRT system on the territory, which is dynamic. This suggests a future line of work focused on exploring and improving the representation of static variables to better approximate the effects of BRT implementation in future iterations of the model.

To calculate distances between transport planning zones (TPZ) and urban facilities, the method of connecting the network between modes through any connection point was established. This tool produces descriptive statistics based on the origin–destination matrix, which is then used to form three groups of results.

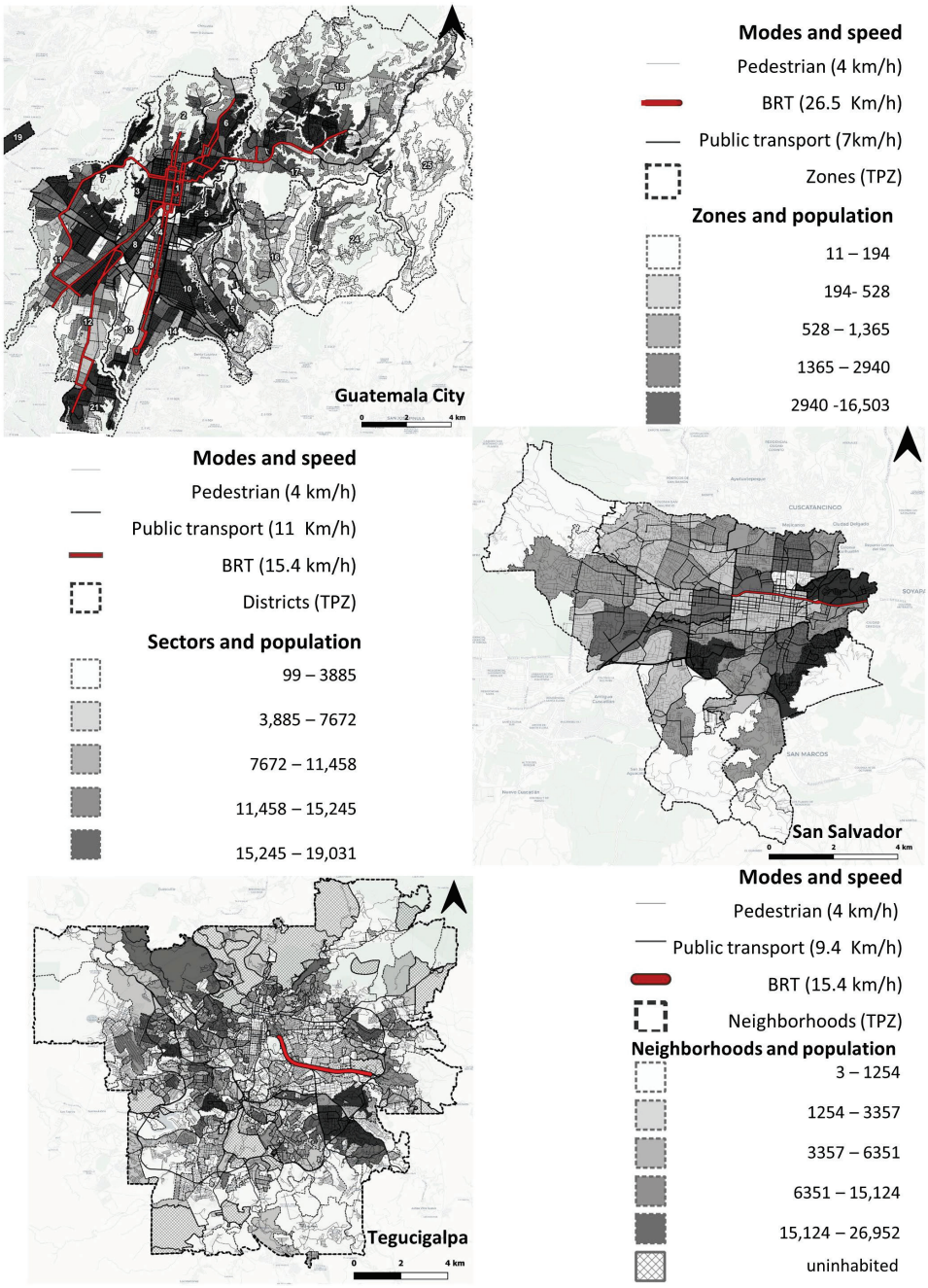



**Figure 4.** Territorial models of NCAT capital cities. Source: Author's elaboration based on multiple sources described in Table 1.

The first group consists of a series of 15 min area maps that display access times to urban facilities before and after BRT projects. These maps quantify the population that is excluded from access to urban facilities. The second group presents spatial efficiency indicators, which describe the population using descriptive statistics over time ranges and evaluate the data dispersion across these ranges through variance. This allows for an analysis of territorial inequalities before and after the BRT project, highlighting differences and territorial exclusions.

Finally, the third set of indicators includes the Gini Index, which as indicated by Van Wee and Mouter [42] is widely used to provide data on equity conditions regarding territorial accessibility. In summary, this indicator contributed to the analysis with an exploratory approach to the accessibility condition towards urban facilities in each capital city of the NCAT, thereby marking the beginning of an incipient analysis in terms of equity.

**Table 1.** Main types of information, characteristics, and data sources.

| Type of Information | TRANSMETRO (Guatemala City) | SITRAMSS (San Salvador) | TRANS-450 (Tegucigalpa) |
|---|---|---|---|
| Pedestrian road network—public transportation routes. | [43] | [44] ** | [8] and Open Street Map [45] *** |
| Municipal territory (Ha) | 22,852.90 [46] * | 7130.20 ** | 20,406.50 [47] |
| Speeds | Pedestrian: 4 km; public transportation: 7 km/h [48]; BRT: 26.5 km/h [10] | Pedestrian: 4 km; public transportation: 11 km/h [6]; BRT: 15.4 km/h [10] | Pedestrian: 4 km; public transportation: 9.4 km/h [8]; BRT: 0 |
| Transportation planning zones (TPZs) | 670 census tracts, $\bar{x}$ = 17.95 Ha, σ = 11.38 ha, min. = 2.01 Ha max. = 117.89 Ha * | 43 sec tors, $\bar{x}$ = 166 Ha, σ = 175 ha min = 19 Ha max. = 980 Ha ** | 675 neighborhoods, $\bar{x}$ = 24.85 Ha, σ = 70.07 ha, min = 0.23 Ha, max. = 1050 Ha [47] |
| Number of schools | 1331 * | 335 ** | 529 *** |
| Amount of public space | 444 * | 280 ** | 306 *** |
| Number of grocery stores/markets | 136 * | 60 ** | 85 *** |
| Number of public health clinics | 38 * | 14 ** | 32 *** |
| General population TPZ, % men–women at the municipal level | Census subsegments [43,46] | Municipal sectors [44] | Colonies or residential neighborhoods [47] |
| Population | 1,204,964 [43] | 351,130 ** | 1,230,850 |
| Urban population in metropolitan area | 5.1 million | 1.8 million | 2.9 million |
| Gross density (Hab/Ha) | 54.35 | 49.24 | 60.32 |

Source: Own elaboration based on multiple sources. Note: The symbols *, **, *** refer to the citation in which they first appear.

In summary, the evaluation process for the accessibility to basic urban amenities utilized the methodology of optimal location models through open-source software. This approach enabled the generation of metrics associating accessibility with indicators such as spatial equity, spatial efficiency, and the Gini Index. This process was conducted for each capital city in the Northern Central American Triangle both before and after the implementation of BRT projects. The aim was to compare the results and deduce the impacts of these projects on improving social sustainability.

Two methodological considerations stand out in conclusion. Firstly, while 15 min maps can be helpful, according to Bertaud [49], they do not fully address the complexities of accessibility, as they do not consider the influence of consumer and labor markets on land use. This information is important for effective communication with decision-makers. Secondly, although the methodology identifies areas of low accessibility and affected populations, it does not identify the situations of vulnerable groups due to limitations in the initial data. However, despite these limitations, the initial identification process enables prioritization of interventions to enhance quality of life, aligning with SSUM by emphasizing population accessibility as a measure of efficiency in urban mobility.

## 3. Results

Figures 5–7 present a visual summary of the results obtained from the accessibility evaluation. Each map displays the locations of urban facilities, using black dots as symbols. The figures demonstrate the evaluations conducted before and after the implementation of the BRT project, except for Tegucigalpa. Despite the construction of a significant part of the infrastructure, the BRT system never operated in Tegucigalpa.

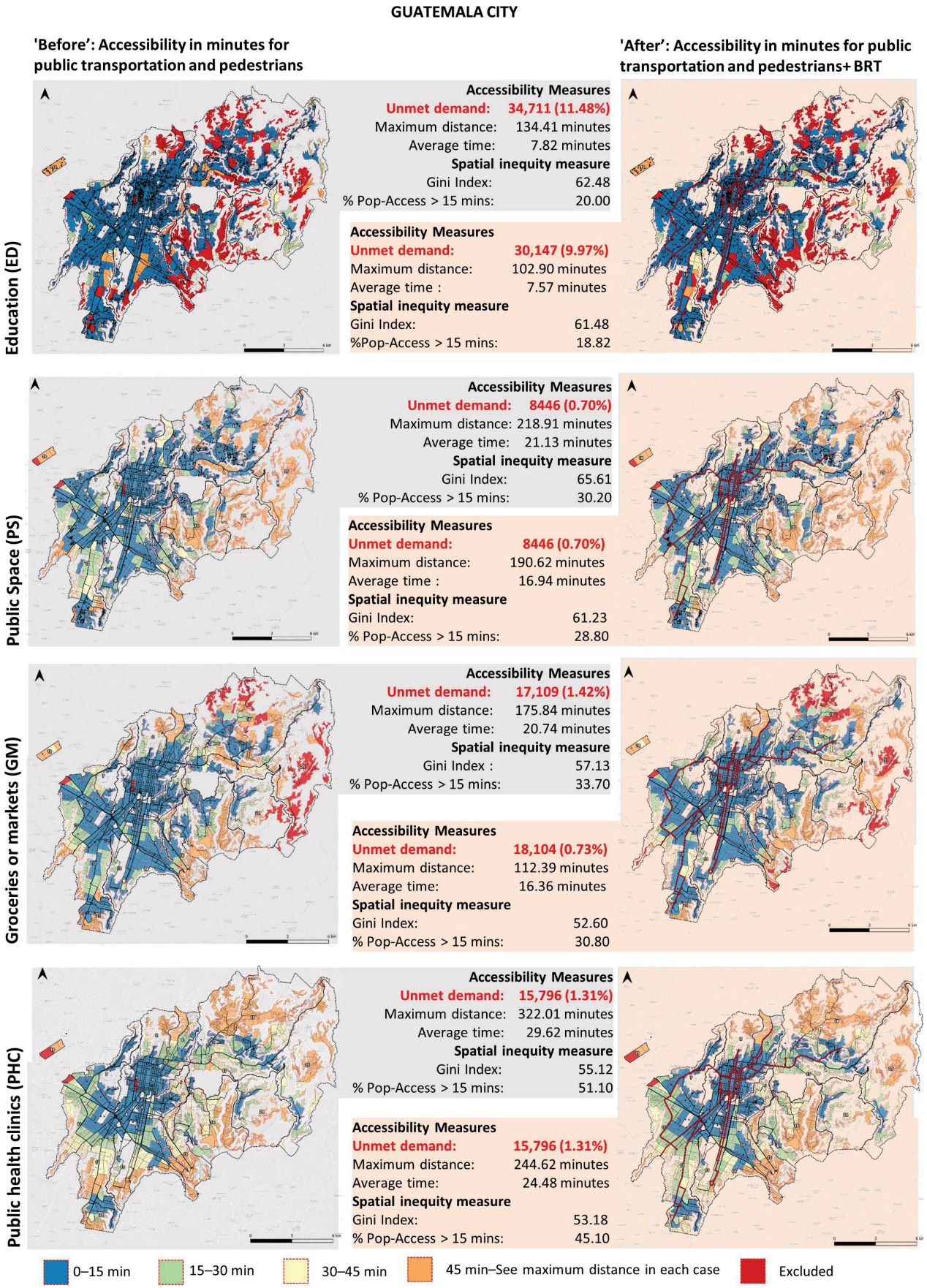



**Figure 5.** Synthesis of accessibility assessments in Guatemala City.

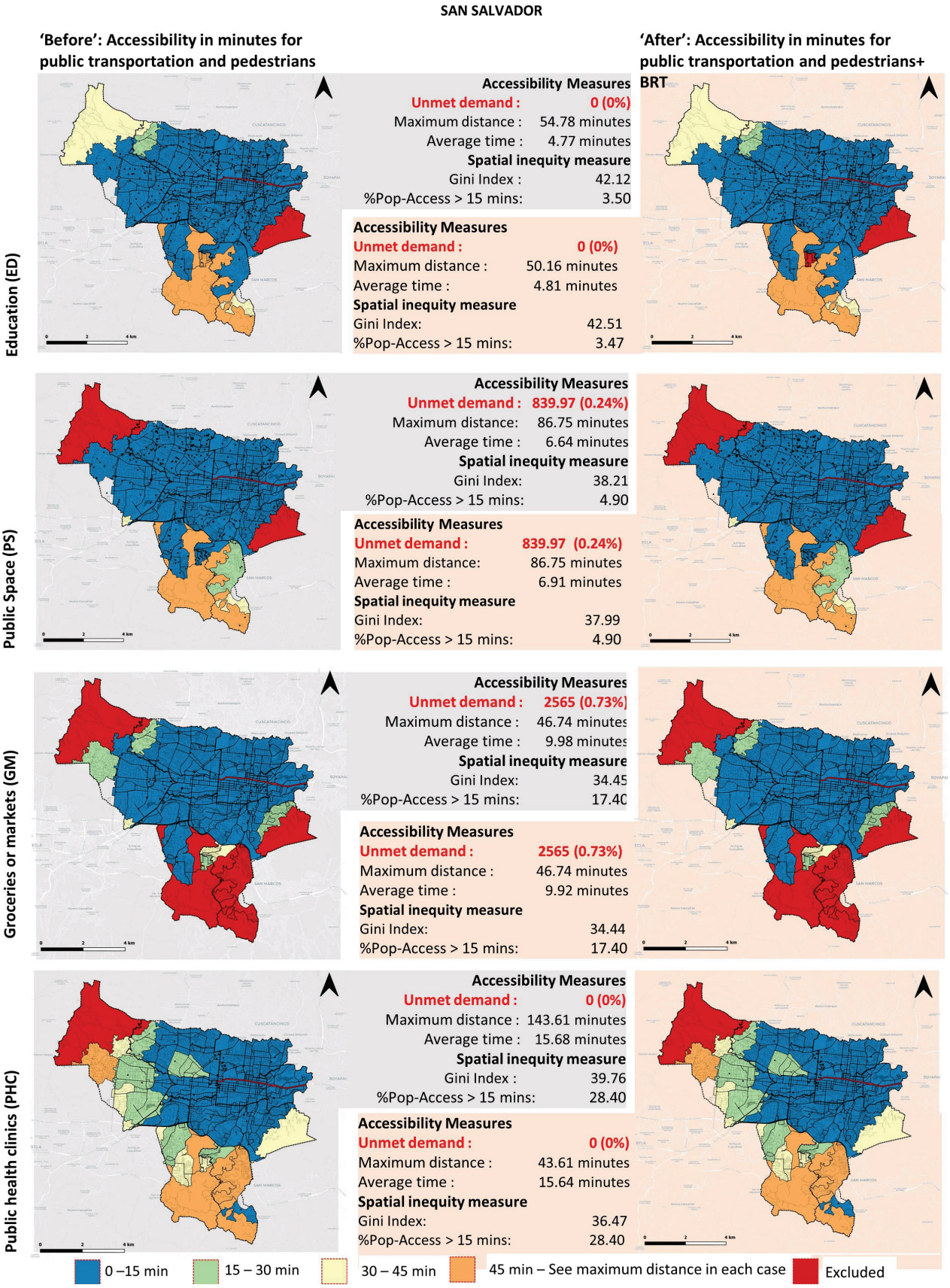



**Figure 6.** Synthesis of accessibility assessments in San Salvador.

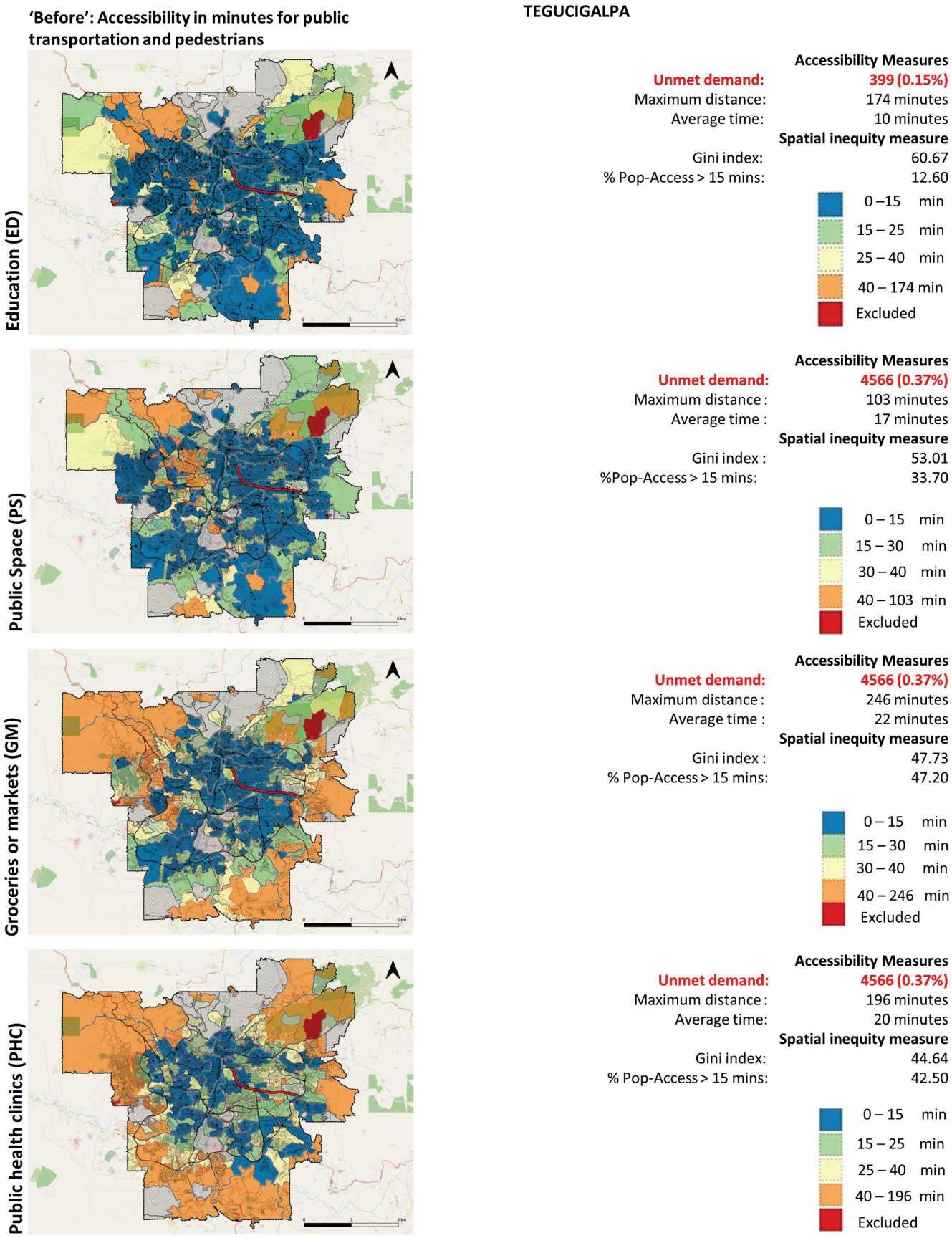



**Figure 7.** Synthesis of accessibility assessments in Tegucigalpa. Note: Red line in figure depicts BRT projected line.

Table 2 presents the results of the accessibility measurements, using the designations B for 'before', A for 'after', and Δ for the difference between before and after. The values in the Δ field are highlighted in red to indicate increases, while green tones indicate reductions in travel time to urban facilities after the implementation of the BRT project. The urban facilities are labelled with the following nomenclature: education facilities (ED), public spaces (PS), grocery stores or markets (GM), and public health clinics (PHC). The results highlight several aspects.

**Table 2.** Synthesis of accessibility indicators for the NCAT capital cities.

| **Indicators/City** | | **Guatemala City** | | | | **San Salvador** | | | | **Tegucigalpa** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Population | | 1,204,964 | | | | 351,130 | | | | 1,230,850 | | | |
| Student population | | 253,283 | | | | 105,023 | | | | 302,325 | | | |
| Urban facility | | ED | PS | GM | PHC | ED | PS | GM | PHC | ED | PS | GM | PHC |
| **Spatial efficiency** | | | | | | | | | | | | | |
| Distance $\bar{x}$ (minutes) | B | 7.83 | 21.12 | 20.75 | 29.62 | 4.77 | 6.94 | 9.98 | 15.68 | 9.11 | 16.84 | 22.1 | 19.57 |
| | A | 7.57 | 16.94 | 16.36 | 24.48 | 4.81 | 6.91 | 9.91 | 15.64 | - | - | - | - |
| | Δ | 0 | 4 | 4 | 5 | 0 | 0 | 0 | 0 | - | - | - | - |
| Max-Min (minutes) | B | 134.4 | 218.6 | 175.8 | 322 | 54.43 | 85.6 | 45.33 | 140.6 | 173.5 | 102.9 | 245.2 | 194.5 |
| | A | 102.9 | 190.3 | 112.4 | 244.6 | 49.8 | 85.6 | 46.74 | 140.6 | - | - | - | - |
| | Δ | 32 | 28 | 63 | 77 | 5 | 0 | −1 | 0 | - | - | - | - |
| σ (minutes) | B | 15.6 | 61.77 | 32.01 | 71.43 | 11.9 | 15.33 | 10.58 | 23.79 | 17.4 | 17.67 | 26.76 | 28.8 |
| | A | 11.33 | 51.87 | 27.67 | 55.66 | 11.8 | 15.33 | 10.58 | 23.8 | - | - | - | - |
| | Δ | 4 | 10 | 4 | 16 | 0 | 0 | 0 | 0 | - | - | - | - |
| **Spatial equity** | | | | | | | | | | | | | |
| Gini Index | B | 62.48 | 65.61 | 57.13 | 55.12 | 42.12 | 38.21 | 34.45 | 39.76 | 60.67 | 53.01 | 47.73 | 44.64 |
| | A | 61.48 | 61.24 | 52.6 | 53.18 | 42.51 | 38 | 34.44 | 39.93 | - | - | - | - |
| | Δ | 1 | 4 | 5 | 2 | 0 | 0 | 0 | 0 | - | - | - | - |
| Population with accessibility over 15 min | B | 50,568 | 363,706 | 406,410 | 616,244 | 3640 | 17,258 | 61,033 | 99,759 | 38,197 | 414,592 | 581,159 | 523,079 |
| | A | 47,661 | 346,615 | 371,399 | 543,523 | 3640 | 17,258 | 61,033 | 99,759 | - | - | - | - |
| | Δ | 2907 | 17,091 | 35,011 | 72,721 | 0 | 0 | 0 | 0 | - | - | - | - |
| % of population with >15-min accessibility | B | 20.00 | 30.20 | 33.70 | 51.10 | 3.50 | 4.90 | 17.40 | 28.40 | 12.60 | 33.70 | 47.20 | 42.50 |
| | A | 18.82 | 28.80 | 30.80 | 45.10 | 3.47 | 4.90 | 17.40 | 28.40 | - | - | - | - |
| | **Δ.** | 1.10 | 1.40 | 2.90 | 6.00 | 0.00 | 0.00 | 0.00 | 0.00 | - | - | - | - |

Source: Authors' own elaboration. Note: For the case of the population living near educational facilities, only the population of school age was considered. The equipment columns correspond to educational facilities (ED), public spaces (PS), grocery stores or markets (GM), and public health clinics (PHC). Accessibility measurements: B: "before"; A: "after"; Δ: difference between before and after. Data are highlighted in traffic light code to point out relations among the results. Red tones indicate increases in travel time among the results, yellow tones indicate intermediate increases, while green tones indicate reductions in travel time to urban facilities after the implementation of the BRT project and positive numbers of persons moved to zones with acceptable levels of accessibility.

Firstly, Guatemala City has the highest absolute levels of travel time to urban facilities among the three cities studied. However, the city has also made significant progress in reducing travel times and increasing access to basic urban facilities within a 15 min radius. Approximately 73,000 people now have improved access to health services and around 2900 students (about 1% of the student population) have better access to education facilities within these zones.

Secondly, Table 2 shows that the TRANSMETRO project in Guatemala has significantly reduced the maximum and minimum time intervals for spatial efficiency, particularly in the southwest and northeast regions, as illustrated in Figure 5. The minimum reduction is 28 min for access to public spaces and the maximum reduction is 77 min for access to health facilities. It should be noted that there are also some reductions in daily travel times in San Salvador (around five minutes), although they may be barely noticeable to someone who travels daily.

Figure 8 illustrates the third result for Guatemala and San Salvador regarding the accessibility before (indicated by blue dots) and after (indicated by red dots) the implementation of the BRT projects. The dot size indicates the population, revealing a significant reduction in travel time to public health clinics that serve a large number of people in Guatemala. In contrast, San Salvador shows only slight decreases in access times.

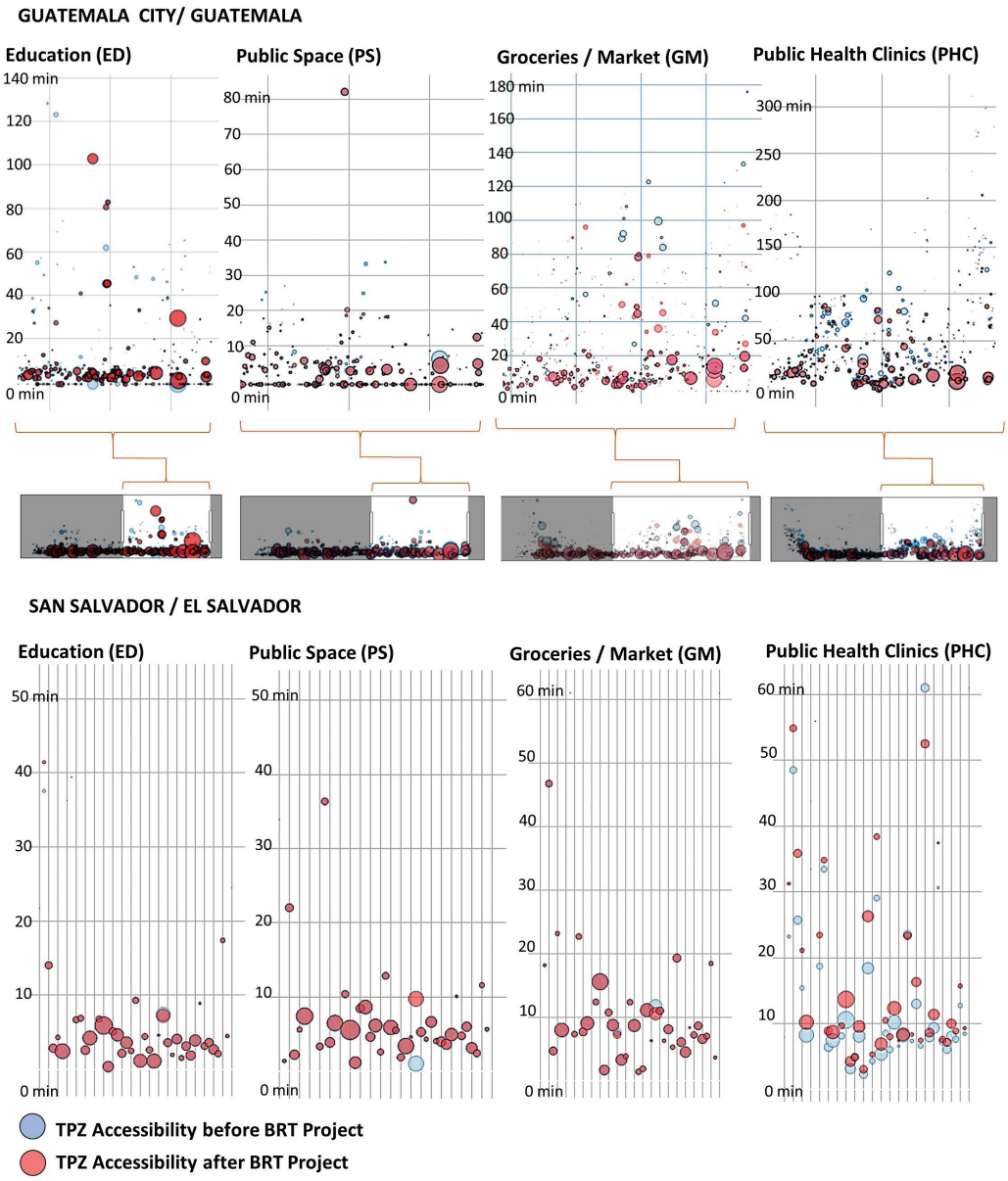



**Figure 8.** Comparison of TPZ accessibility values in Guatemala and San Salvador before and after BRT projects. Source: From the authors. Note: The sizes of circles representing TPZs are proportional to the population they contain in relation to the total population of the municipality. *Y*-axis shows travel time and *X*-axis is an individual code for each TPZ. For a more detailed view of the graphs in this Figure, you can access the following link: http://bit.ly/3KidLbj (accessed on 1 January 2021).

This evidence highlights the importance of accessibility as a critical measure for evaluating social sustainability. It confirms that the expansion of the TRANSMETRO network has resulted in improved travel times, enabling more people to access essential facilities within a 15 min radius.

The fourth significant finding concerns the SITRAMSS project in San Salvador. Table 2 indicates a minor improvement in travel times, although this is hardly noticeable. As previously mentioned, the impact is mostly negative. This is due to the fact that the constructed section of six kilometers was designed as a 'showcase' area, providing travel benefits for those living outside the municipality but not enhancing the daily life quality of the local residents. In summary, unlike TRANSMETRO, there are limited local benefits to accessing basic urban facilities.

The fifth result shows that the TRANS-450 project in Tegucigalpa has negative values for the 15 min zones, similar to the situation with SITRAMSS. Despite significant investment, TRANS-450 did not improve accessibility as it did not function, indicating a lack of contribution to the social aspect of sustainability.

## 4. Discussion

The key findings indicate a modest but significant improvement in the municipality of Guatemala in terms of the equity and spatial efficiency of access to basic urban facilities, especially health services and markets, after the BRT project's development (see Table 2). Despite the longer travel times and wider temporal gaps observed in the spatial efficiency indicators (see Max–Min and σ indicators in Table 2), TRANSMETRO, compared to the other two studied countries' systems, is currently the only project that has effectively reduced these gaps in spatial efficiency and equity.

In Guatemala, the population has improved the travel times to all urban facilities, particularly public health clinics. Approximately 6% of the capital's population, around 72,700 people, are estimated to be within a 15 min radius of a public health clinic. It is noteworthy that the Gini Index, as an indicator of equity, shows reductions in the access gaps to all urban facilities, especially market facilities, of up to 5 points. These improvements can be perceived via their respective variations in each TPZ, impacting the overall promotion of social sustainability, facilitating the creation of sustainable communities, and improving quality of life.

Regarding the SITRAMSS project in San Salvador, despite operating for nearly six years, it did not lead to any significant improvement in population access to basic urban facilities, as evidenced by the spatial efficiency and equity indicators. The TRANS-450 (Tegucilapa) project shows absolute accessibility values comparable to those of Guatemala City, although in terms of its progress in reducing the equity gap, it resembles the Salvadoran case. Therefore, it failed to have an impact on the population, even though it received significant infrastructure investments and remained inoperative.

These cases highlight that an investment in public transportation does not always solve the problem of accessibility, particularly when there is not successful integration with the existing urban fabric and infrastructure. The fragmented city has remained but with new challenges to beat due to changes introduced by the new transport infrastructure.

In this regard, the results obtained in Guatemala align with other ex post evaluations of BRT systems [50], suggesting that the successful integration of BRT systems into the existing public transport network and urban environments can achieve positive redistributive effects, especially for lower-income strata of society. TRANSMETRO [16] aimed to achieve this dual integration (existing public transport–urban environment), and these findings are in line with evaluations in the southwest axis [51]. It is, therefore, asserted that TRANSMETRO has contributed significant benefits in regions where middle-income residents tend to use private transport. Based on these results and those shown in Table 2 and Figure 5, indicating greater accessibility in the TPZs and the expansion of TRANSMETRO, the municipality of Guatemala is fostering equity by quickly connecting urban facilities to the entire population.

This assertion could be interpreted as a utilitarian approach to improving accessibility based on one of the theories provided by Pereira et al. [52], i.e., that access is improved without prioritization among beneficiary social groups. However, it could also be conjectured that vertical equity is achieved for at least two reasons.

The first reason, depicted in Figures 5–7, is that the TRANSMETRO project covers a broad territorial network, in contrast to the single-line structures of SITRAMSS and TRANS-450. This provides access to areas that previously lacked efficient transport services. The second reason is that while the outskirts of the NCAT capital cities may contain low-density housing developments for middle- to high-income families, it is also common to find lower-income strata on the peripheries. For the time being, this point represents a starting hypothesis for future lines of research that involve identifying the accessibility situations of vulnerable groups in order to confirm that at least low-income residents have benefited.

In terms of a comparative analysis, it was established that the central areas of the NCAT capitals were well-served both before and after BRT projects (see Figures 5–7). However, as we move away from the center, the quality of access to various services deteriorates. This aligns with the findings of Pitarch-Garrido [24] for the city of Valencia, which suggest that accessibility improvements are extended as transport lines create axes of improvement in the areas near the main corridors.

Within the context of the NCAT, a noteworthy finding is the lack of recognition of the importance of non-motorized mobility (NMM) modes when assessing accessibility, implementing mass transport projects, and overseeing them. Although NMMs are frequently used in the NCAT, their implementation is not addressed with the necessary urgency. For example, Guatemala expressed initial interest in the BRT development plan [16] but faced criticism for not prioritizing NMM infrastructure in the execution of TRANSMETRO [53].

This study contributes by integrating NMMs into the evaluation and planning in the territorial model development process. The results from Table 2 are a consequence of the influence of pedestrian modalities on accessibility and their importance in a multimodal journey. However, there is still a need for more in-depth integration of NMMs. Additionally, it can be affirmed that in peripheral regions where BRT corridors fail to improve accessibility, NMMs are a viable alternative to complement journeys. However, achieving this requires coordination with motorized transport systems and the implementation of institutional policies, at least in terms of management, citizen participation, regulations, and infrastructure, as recommended in [54].

Finally, in order to add nuance to this assessment of accessibility in the NCAT, three aspects need to be considered. Firstly, the results may be considered optimistic due to the lack of data to anticipate wait times when changing modes. Nevertheless, it is crucial to consider this initial assessment as a benchmark for accessibility in the NCAT until accessibility indicators can provide enough information for policymakers to recognize the diversity of people's needs and constraints when making their transportation decisions, as confirmed by Pereira et al. [52].

Second, it highlights the inherent challenge of the SSUM assessment process, as databases do not allow for the segregation of vulnerable groups. It is crucial to emphasize the significant hurdle of conducting this type of research in cities of the Global South, which are characterized by limited access to information and a lack of systematized, especially georeferenced data.

Muente-Kunigami [55] argues that the Latin American region can be compared to Africa and Asia in terms of its lowers scores in indicators such as Global Open Data Index, Open Data Inventory, and Open Data Barometer, which assess countries' strategies for implementing open government data.

Thirdly, the degree of accessibility identified for each TPZ and its urban facilities does not allow the identification of zones with vulnerable populations, such as for education. Factors such as quality, age-segmented data, and the required level of equipment are aspects to prioritize for future improvements.

## 5. Conclusions

In order to respond to the research question and as a generalization, this article presents two non-exclusive alternatives on how accessibility assessments can be used to evaluate progress in the social sustainability of urban mobility, under conditions of low investment in tools and scarce data, which are recurrent in the Global South.

The first alternative involves obtaining indicators of the spatial efficiency of the urban facilities and transport systems through the assessment of accessibility before and after the implementation of urban mobility projects. This assessment method seeks to identify differentials in impedances (e.g., descriptive statistics of time, distance, money) caused to individuals. These differentials, examined in light of a reference threshold (e.g., a fifteen minute city, minimum wage) will represent progress or regression in the distribution of benefits from transportation systems.

The second alternative pertains to the evaluation of spatial equity. As discussed, it is possible to infer certain impacts on the horizontal and vertical equity levels of transport system users from cartographic and statistical indicators. This article proposes the Gini Index as a global indicator and percentages of individuals included in post-implementation tolerance thresholds as comparative indicators; these results may be more useful if they are matched with additional data on population characteristics such as income level, gender, disability, and age.

On the other hand, it is particularly noteworthy for the capital cities of the NCAT that despite the three BRT projects being developed in similar contexts, the outcomes vary significantly. TRANSMETRO has enhanced the accessibility to basic urban facilities, a crucial element of SSUM. However, an improvement in accessibility alone is not sufficient for SSUM; it is imperative that this enhancement exhibits two key characteristics. Firstly, there must be a noticeable improvement in spatial equity, manifested in reductions in time when accessing basic facilities in various areas of the city. Secondly, the inclusion of population sectors previously distant from an evaluation threshold is needed—conditions observed in Guatemala City.

In comparison with SITRAMSS and TRANS-450, the TRANSMETRO project stands out in terms of both its accessibility indicators (efficiency and spatial equity) and morphological characteristics as a wide-reaching network, with acceptable urban integration into the existing public transport network and built environment and efficient management that allowed for rapid expansion.

These characteristics have had far-reaching effects, including a 70% reduction in air pollution in the southwest axis [56], time savings for residents, and economic and social gains through improved access to existing facilities, avoiding the need for new construction projects. In contrast, SITRAMSS and TRANS-450 have not made progress in terms of accessibility indicators and have experienced a slow and concentrated implementation strategy in specific areas of the territory. Overall, these features highlight TRANSMETRO as a desirable and influential project for improving SSUM and implementing a BRT system.

However, to identify key issues for policy-making, it is essential to evaluate the impact of SUMM on the distribution of benefits among the population in the capital cities of the NCAT. This paper proposes a methodology that can be considered a benchmark for assessing accessibility, as it recognizes the availability of data and resources in the NCAT capital cities.

Nevertheless, this evaluation is preliminary, although it is valuable for planners and decision-makers as it identifies the evolution of the benefits resulting from the reduction in barriers to accessing basic urban services generated by BRT projects. Despite the limitations in identifying vulnerable groups and the impacts on commuting due to information constraints, this equity assessment is novel and provides data on the current situation, factors influencing progress, and identified areas that have benefited and those that require more attention.

Regarding the falsifiability of the hypothesis, the initial results and the detailed conclusions of this article describe at least one of the three elements of SSUM in greater detail, specifically addressing how improvements in accessibility impact the construction

of a sustainable community. In this context, Guatemala City serves as a clear example, as the changes brought about by the implementation of its BRT system directly influenced situations of inclusion for individuals, particularly among populations previously lacking services. This improvement in access times to basic needs contrasts notably with the other two case studies.

Finally, regarding future research directions related to policy-making and the research presented in this paper, three areas emerge from the perspective of the Global South. The first relates to identifying how these improvements in inclusion and equity conditions impact the fight against poverty, an outstanding goal of sustainable development. As Godard [57] points out, urban mobility policies and projects are an exceptional tool in the fight against poverty, and not using them in this way in Global South urban mobility projects would be a missed opportunity.

The second line of research concerns the interaction between SSUM evaluations and the environmental and economic dimensions of sustainable development. Moreno and Colsa [58] propose indicators that assess carbon emissions generated by travel, while Garretón [59] suggests techniques that prioritize the identification of economically disadvantaged sectors, both stemming from accessibility assessments.

The two lines described above are complementary when diving into more comprehensive evaluations of accessibility, including data for socioeconomic and environmental issues, which this time could not be included due to a scarcity of information.

Finally, a third line of inquiry should seek to refine the territorial model presented in this article with improvements to the database, detailing the calculation of impedances and determining strategies to identify vulnerable groups. This could enable the development of a more sophisticated calculation of accessibility.

Additionally, delving deeper into the characteristics of urban amenities that can act as deterrents or attractors is essential. For example, in the case of education, the quality of education is important when deciding which educational institution to attend or to what extent groceries and markets promote food deserts. In this regard, refining these and other aspects will provide a comprehensive understanding of urban mobility and its impacts in the NCAT capital cities.

**Funding:** This research was funded by Universidad Loyola Andalucía and Universidad Centroamericana José Simeón Cañas through a scholarship for PhD studies given by both institutions.

**Institutional Review Board Statement:** The data used in the research were obtained directly from the institutions of each country, which are detailed in Table 1. This means that no interviews were conducted, nor was direct contact established with people or animals. Therefore, according to the regulations of the Universidad Loyola Andalucía, which can be consulted at this link: https://www.uloyola.es/investigacion/comite-de-etica-de-la-investigacion, it was not necessary to validate this data through the institutional ethics committee.

**Informed Consent Statement:** Not applicable. The data used for the research were directly obtained from the institutions cited in the article and did not involve interviews or direct contact with individuals or animals, making it unnecessary to validate it through the institutional ethics committee.

**Data Availability Statement:** The data presented in this study are available upon request to the corresponding author. They are not publicly accessible due to confidentiality and usage restriction agreements established between the central and local government institutions in the capitals of the NCAT and the researcher.

**Acknowledgments:** Special thanks are given to Carlos Manzano, Alex Renderos, and Carlos Ferrufino for their comments on this article and to the Universities of Loyola Andalucía and Centroamericana José Simeón Cañas for their institutional and financial support for the research and publication of this manuscript. Finally, gratitude is extended to the Municipal Directorate of Geographic Information and the Urban Mobility Directorate, both from Guatemala City, the Energy Research Institute of the Autonomous University of Honduras, and the Office of Planning of the Metropolitan Area of San Salvador for their willingness to share the information.

**Conflicts of Interest:** The author declares no conflict of interest.

## References


1. Colantonio, A. Social Sustainability: A Review and Critique of Traditional versus Emerging Themes and Assessment Methods. *SUE-MoT Conf.* **2009**, *2009*, 865–885.
2. McKenzie, S. *Social Sustainability: Towards Some Definitions*; Hawke Research Institute, University of South Australia: Magill, South Australia, 2004.
3. Shirazi, R.; Keivani, R.; Shirazi, M.R.; Keivani, R. Social Sustainability Discourse: A Critical Revisit. In *Urban Social Sustainability: Theory, Policy and Practicepolicy*; Shirazi, R., Keivani, R., Eds.; Routledge: New York, NY, USA, 2019; pp. 1–26. ISBN 9781138069381.
4. Zegras, C. Mainstreaming Sustainable Urban Transport: Putting the Pieces Together. In *Urban Transport in the Developing World: A Handbook of Policy and Practice*; Dimitriou, H.T., Gakenheimer, R., Eds.; Edward Elgar Publishing: Cheltenham, UK, 2011; pp. 548–588. ISBN 9781847202055.
5. Dimitriou, H. Transport and City Development: Understanding the Fundamentals. In *Urban Transport in the Developing World. A Handbook of Policy and Practice*; Edward Elgar Publishing: Cheltenham, UK; Northhampton, MA, USA, 2011; pp. 8–39.
6. Nevo, M.; Granada, I.; Ortiz, P. *SITRAMSS: Mejorando El Transporte Público Del Área Metropolitana de San Salvador*; BID: Tegucigalpa, Honduras, 2016.
7. Palma, J. Eje de Movilidad Urbano Sostenible y Ordenamiento Territorial. In *Estado del Arte de la Movilidad y Desarrollo Urbano Sostenible en Honduras*; Castellanos, E., Palma, J., Valladares, R., Cabrera, G., García, E., Eds.; Dirección de Investigación Científica y Postgrado, Universidad Autónoma de Honduras: Tegucigalpa, Honduras, 2018; pp. 51–176.
8. BID; ALG; Le Vote. *Estudio de Apoyo Al Plan de Movilidad Urbana Sostenible (PMUS) Para El Distrito Central de Tegucigalpa y Comayagüela. Informe Final*; BID: Tegucigalpa, Honduras, 2012.
9. Flyvbjerg, B. What You Should Know about Megaprojects and Why: An Overview. *Proj. Manag. J.* **2014**, *45*, 6–19. [CrossRef]
10. Global BRT Data Base de Datos 2023. Available online: https://brtdata.org/ (accessed on 17 January 2024).
11. Neki, K.; Mitra, S.; Wambulwa, W.M.; Job, R.F.S. Profile of Low and Middle-Income Countries with Increases versus Decreases in Road Crash Fatality Population Rates and Necessity of Motorcycle Safety. *J. Safety Res.* **2023**, *84*, 129–137. [CrossRef] [PubMed]
12. INE Instituto Nacional de Estadística 2021. Available online: https://ine.gob.hn/v4/ (accessed on 1 January 2022).
13. SAT Super Intendencia de Administración Tributaria. Available online: https://portal.sat.gob.gt/portal/ (accessed on 1 January 2022).
14. VMT Observatorio Nacional de Seguridad Víal. Available online: https://observatoriovial.fonat.gob.sv/parque-vehicular/ (accessed on 19 October 2023).
15. COAMSS-OPAMSS. *Política Metropolitana de Movilidad Urbana, Hacia Una Movilidad Sostenible, Equitativa, Segura, Inclusiva y Eficiente*; COAMSS-OPAMSS: San Salvador, El Salvador, 2020; p. 56.
16. EMT; DMU; STP; Municipalidad de Guatemala; EMETRA. La Historia de Nuestro TRANSMETRO—Ciudad de Guatemala. 2015.
17. Lineburg, K. *Transportation Rating Systems and Social Sustainability: A Comprehensive Analysis*; College of Integrated Science and Engineering James Madison James Madison University: Harrisonburg, VA, USA, 2016.
18. Vallance, S.; Perkins, H.C.; Dixon, J.E. What Is Social Sustainability? A Clarification of Concepts. *Geoforum* **2011**, *42*, 342–348. [CrossRef]
19. Polèse, M.; Stren, R.E. *The Social Sustainability of Cities: Diversity and the Management of Change*; University of Toronto Press: Toronto, ON, Canada, 2000.
20. Dempsey, N.; Bramley, G.; Power, S.; Brown, C. The Social Dimension of Sustainable Development: Defining Urban Social Sustainability. *Sustain. Dev.* **2011**, *19*, 289–300. [CrossRef]
21. Flora, J. Management of Traffic and the Urban Environment. In *the Challenge of Urban Government: Policies and Practices*; The World Bank: Washington, DC, USA, 2001; pp. 383–394.
22. Cervero, R. Transport Infrastructure and the Environment in the Global South: Sustainable Mobility and Urbanism. *J. Perenc. Wil. dan Kota* **2014**, *25*, 174–191. [CrossRef]
23. Ferrell, C.E.; Reinke, D.; Eeels, J.M.; Schroeder, M.M. *Defining and Measuring Equity in Public Transportation*; Mineta Transportation Institute: San José, CA, USA, 2023.
24. Pitarch-Garrido, M.D. Social Sustainability in Metropolitan Areas: Accessibility and Equity in the Case of the Metropolitan Area of Valencia (Spain). *Sustainability* **2018**, *10*, 371. [CrossRef]
25. Armstrong, B.; Davison, G.; de Vos Malan, J.; Gleeson, B.; Godfrey, B. *Delivering Sustainable Urban Mobility*; Australian Council of Learned Academies: Melbourne, Australia, 2015.
26. Ortúzar, J. Sustainable Urban Mobility: What Can Be Done to Achieve It? *J. Indian Inst. Sci.* **2019**, *99*, 683–693. [CrossRef]
27. Dobranskyte-Niskota, A.; Perujo, A.; Jesinghaus, J.; Jensen, P. *Indicators to Assess Sustainability of Transport Activities Part 2: Measurement and Evaluation of Transport Sustainability Performance in the EU27*; JRC Publications Repository: Ispra, Italy, 2009.
28. Littig, B.; Griessler, E. Social Sustainability: A Catchword between Political Pragmatism and Social Theory. *Int. J. Sustain. Dev.* **2005**, *8*, 65–79. [CrossRef]
29. Pitarch, M. Measuring Equity and Social Sustainability Through, The Case of the Metropolitan Area of Valencia (Spain). *Eur. J. Geogr.* **2013**, *4*, 64–85.
30. Maria, A.; Acero, J.L.; Aguilera, A.I.; Garcia Lozano, M. *Central America Urbanization Review: Making Cities Work for Central America*; World Bank: Washington, DC, USA, 2017.

31. Danermark, B.; Ekström, M.; Karlsson, J.C. Critical Me Thodological Pluralism—Intensive and Extensive Research Design and Interdisciplinarity. In *Explaining Society: Critical Realism in the Social Sciences*; Routledge: London, UK, 2019; pp. 165–196.
32. Orozco-Montoya, R.; Vargas-Bolaños, C.; Vargas-Hernández, A.; Aguilar-Arias, J. *Crecimiento de Las Principales Áreas Metropolitanas de Centroamérica*; Programa Estado de la Nación: San José, Costa Rica, 2015.
33. Goodall, B. *The Economics of Urban Areas*; Elsevier: Amsterdam, The Netherlands, 2013; Volume 3.
34. Camagni, R. *Economía Urbana*, 1st ed.; Antoni Bosch: Barcelona, Spain, 2005; ISBN 8495348136.
35. Trenc, J.E.; Cebollada, A.; Miralles-Guasch, C. Percepciones de La Movilidad y Participación Ciudadana En La Región Metropolitana de Barcelona. *Ciudad y Territ. Territ.* **2008**, *XL*, 499–510.
36. Geurs, K.T.; Van Wee, B. Accessibility Evaluation of Land-Use and Transport Strategies: Review and Research Directions. *J. Transp. Geogr.* **2004**, *12*, 127–140. [CrossRef]
37. Hansen, W.G. How Accessibility Shapes Land Use. *J. Am. Plan. Assoc.* **1959**, *25*, 73–76. [CrossRef]
38. Moreno, A. Modelos de Localización Óptima y Planificación Territorial: Sinopsis Teórico-Metodológica. In *Sistemas de Información Geográfica: Aplicaciones en Diagnósticos Territoriales y Decisiones Geoambientales*; Moreno, A., Buzai, G., Fuensalida, M., Eds.; Ra-Ma: Madrid, Spain, 2017; pp. 255–268. ISBN 978-84-9964-639-8.
39. De Jong, T.; Vaart, V. der Flowmap 2013. Available online: https://flowmap.nl/ (accessed on 1 January 2020).
40. Batista, T.; Caballero, C.; Ceballos, F.; Carriço, C.; Mateus, J.; Lopes, H.; White, P.V.; Cabezas, J.; Fernández, L.; Pinto-Gomes, C. IDE-OTALEX C. The First Crossborder SDI between Portugal and Spain: Background and Development Grande Rota Do Montado View Project IDE-OTALEX C. The First Crossborder SDI between Portugal and Spain: Background and Development. *J. Earth Sci. Eng.* **2013**, *3*, 393–400. [CrossRef]
41. DIGESTYC. *Encuesta de Hogares y Propósitos Múltiples Del Año 2019*; DIGESTYC: San Salvador, El Salvador, 2020.
42. Van Wee, B.; Mouter, N. Evaluating Transport Equity. In *Advances in Transport Policy and Planning*; Academic Press: Cambridge, MA, USA, 2021; Volume 7, pp. 103–126. ISBN 9780323855594.
43. DMU. *Bases de Datos, Dirección de Movilidad Urbana Ciudad de Guatemala*; DMU: Ciudad de Guatemala, Guatemala, 2021.
44. OPAMSS. *Datos Del Observatorio*; OPAMSS: San Salvador, El Salvador, 2021.
45. Geofabrik, D.S. Open Street Map. Available online: https://www.geofabrik.de/geofabrik/openstreetmap.html (accessed on 1 October 2021).
46. Dirección Municipal de Información Geográfica Bases de Datos 2021. This database is not available to the public and was granted by the municipality.
47. Instituto de Investigación en Energía Bases de Datos 2020. This database is not available to the public and was granted by the municipality.
48. ANADIE Sistema de Transporte Público Masivo Del Eje Oriente-Occidente Del Área Metropolitana de Guatemala. Available online: https://drive.google.com/file/d/18qFXHKO37amhr2EeaEOhF2ciO_AsxiId/view (accessed on 1 October 2021).
49. Bertaud, A. *The Last Utopia: The 15-Minute City*; Urban Reform Institute: Houston, TX, USA, 2022.
50. Hidalgo, D.; Muñoz, J.C. Bus Rapid Transit and Buses with High Levels of Service: A Global Overview. In *Handbook on Transport and Development*; Elgar Online: Northampton, MA, USA, 2015.
51. Rodriguez, D.A.; Vergel-Tovar, C.E. Urban Development around Bus Rapid Transit Stops in Seven Cities in Latin-America. *J. Urban.* **2018**, *11*, 175–201. [CrossRef]
52. Pereira, R.H.M.M.; Schwanen, T.; Banister, D. Distributive Justice and Equity in Transportation. *Transp. Rev.* **2016**, *37*, 170–191. [CrossRef]
53. Morán, A.; Aragón, J. *Movilidad Urbana Sostenible Para El Área Metropolitana de Ciudad de Guatemala*; Peláez Almengor, Ó., Ed.; CEUR USAC: Ciudad de Guatemala, Guatemala, 2022; ISBN 978-9929-592-46-9.
54. Ríos, R.; Taddia, A.; Pardo, C.; Lleras, N. *Ciclo-Inclusión En América Latina y El Caribe: Guía Para Impulsar El Uso de La Bicicleta*; BID: Santiago, Chile, 2015.
55. Muente-Kunigami, A.; Serale, F. *Los Datos Abiertos En América Latina y El Caribe*; BID: New York, NY, USA, 2018.
56. Castellón, C.; Vélez, J.P.; Landazuri, C.; Martel, J.; Vecco, C. *Estructuración Proyecto Transmetro Eje Nor-Oriente*; BID: New York, NY, USA, 2008.
57. Godard, X. Poverty and Urban Mobility: Diagnosis toward a New Understanding. *Urban Transp. Dev. World A Handb. Policy Pract.* **2011**, 232–261.
58. Moreno Jiménez, A.; Colsa Pérez, A. El Modelo P-Mediano Como Ayuda a Una Planificación Urbana Eficiente y Sostenible. In *Sistemas de Información Geográfica: Aplicaciones en Diagnósticos Territoriales y Decisiones Geoambientales*; Moreno Jiménez, A., Buzai, G.D., Fuenzalida Días, M., Eds.; Ra-Ma: Madrid, Spain, 2012; pp. 309–326. ISBN 978-84-9964-131-7.
59. Garretón, M. Desigualdad Espacial y Utilidad Social: Esfuerzos de Movilidad y Accesibilidad En El Gran Santiago. *Territorios* **2011**, 35–64.


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Review*

# A Review of Attention Restoration Theory: Implications for Designing Restorative Environments

**Yiwen Liu [1], Junjie Zhang [1], Chunlu Liu [2] and Yang Yang [1,*]**

[1] School of Architecture and Urban Planning, Shandong Jianzhu University, Jinan 250000, China; 2021055204@stu.sdjzu.edu.cn (Y.L.); jj7212@sdjzu.edu.cn (J.Z.)
[2] School of Architecture and Built Environment, Deakin University, Melbourne 3220, Australia; chunlu.liu@deakin.edu.au
* Correspondence: yangyang21@sdjzu.edu.cn

**Abstract:** The promotion and development of healthy cities are vital for enhancing human habitats and fostering sustainable economic growth. Based on the core databases of Web of Science, PubMed, Google Scholar, and PsycINFO, and the knowledge graph software, this paper presents a quantitative analysis of the literature related to attention recovery abroad. It is found that in recent years, the research on attention recovery has developed rapidly, the number of related studies has been increasing, and the research content presents the characteristics of interdisciplinary integration. By further analyzing the characteristics of the research literature, research context, and knowledge basis, this paper summarizes the empirical research based on the existing quantitative analysis, reviews the research field based on the mechanism of attention recovery, and analyzes the development process and trend based on the research basis of attention recovery. Due to the change in the modern life style, human health problems are becoming more and more prominent. Attention restoration design provides a new research idea and method to balance the relationship between humans and the urban environment.

**Keywords:** attention recovery; pressure recovery; healthy; quantitative analysis

**Citation:** Liu, Y.; Zhang, J.; Liu, C.; Yang, Y. A Review of Attention Restoration Theory: Implications for Designing Restorative Environments. *Sustainability* **2024**, *16*, 3639. https://doi.org/10.3390/su16093639

Academic Editor: Boris A. Portnov

Received: 20 March 2024
Revised: 22 April 2024
Accepted: 24 April 2024
Published: 26 April 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The information age has ushered in intensified social competition. Modern lifestyles have undergone significant changes, resulting in various public health issues. Compact urban environments and the stressful modern urban lifestyle are significant contributors to mental and chronic illnesses. Consequently, the promotion and development of healthy cities are vital for enhancing human habitats and fostering sustainable economic growth. To attain the objective of a health-focused built environment, the worldwide construction industry has prioritized the integration of health concepts into spatial design. The United States has developed the "WELL Healthy Building" evaluation standard, specifically designed to assess the mental and physical health implications of the built environment. To proactively and effectively tackle current prevalent health issues, China has formulated and issued documents related to Healthy China Action [1]. The emergence of concepts such as "healthy city", "healthy community", and "healthy building" has ushered the health concept into the realm of architectural environmental design. Spatial environment design places greater emphasis on enhancing the comfort and enjoyment of the spatial experience.

Scholars have demonstrated that the environment can indeed influence the mental health and attention levels of residents [2]. Prolonged residence in a low-quality environment not only results in various physical and mental health issues, but also leads to reduced work efficiency, enthusiasm, and other adverse effects. Since the 1980s, numerous studies have demonstrated that natural environments can restore attention and alleviate stress [3]. The information overload and stressful urban environments in modern cities expedite the

depletion of individuals' attention resources. A rising demand for rejuvenating environments in the future is anticipated. It is worth highlighting that substantial attention has been directed toward the concept of "attention recovery", which initially emerged within the realm of environmental psychology. In the last three decades, attention-related research has revolved around two primary theories: Stress Reduction Theory (SRT) and Attention Restorative Theory (ART). Roger Ulrich introduced SRT in 1979 [4], while Stephen Kaplan introduced ART in 1983 [5]. Table 1 displays the evolution of pertinent attention recovery theories. SRT centers on immediate and unconscious emotional reactions induced by the environment [6]. ART concentrates on cognitive responses and posits that exposure to nature can facilitate the restoration of depleted directed attention resources, alleviating cognitive fatigue. SRT and ART are not mutually exclusive, and both share a common foundation in biophilic concepts [5].

**Table 1.** Development process of relevant theories of attention recovery.

| Theory | | | Author | Time | Content |
|---|---|---|---|---|---|
| Theories related to attention recovery | Stress Reduction Theory (SRT) | | Roger Ulrich | 1979 | When an individual is in a state of stress or stress, exposure to some natural environment can alleviate the physical, psychological, and behavioral damage caused by the stressor. |
| | Attention Restorative Theory (ART) | Autonomous attention and involuntary attention concepts | William James | 1892 | William James developed the concept of voluntary attention and involuntary attention. When the object itself is not attractive but one has to pay attention to it, people mobilize autonomous attention, and vice versa. |
| | | Concept of directed attention | Messalam | 1985 | Directed attention, which is similar to undirected attention, is considered important for human health in modern neuromedicine. |
| | | Put forward the theory and the characteristics of the recovery environment | Stephen Kaplan | 1983 | To refine the theoretical framework and fascination, Kaplan added three other features to the restorative environment—being away, extent, and compatibility. |
| | | Psychological perspectives and natural experience | Stephen Kaplan | 1989 | The environment restores directed attention by providing certain qualities and provides individuals with opportunities for contemplation. This process is called a restorative experience. Accordingly, such an environment is a restorative environment. |
| | | Integration of the natural recovery benefit framework | Stephen Kaplan | 1995 | Strong and continuous use of directed attention will lead to the consumption of this resource, causing individuals to make frequent errors and engage in impulsive behavior; but in a restorative environment, individuals can effectively recover attention. |

Over the past decade, an increasing number of studies have emerged from various fields, including environmental psychology, health psychology, and sports psychology [7]. Analyzing spatial quality through the lens of attention restoration design is beneficial for advancing research. Investigating human psychology and behavior allows researchers to comprehend how enhancing the built environment can contribute to the enhancement that enhance human cognitive function and attention restoration capabilities. The fundamental attributes of a restorative environment serve as a theoretical foundation for crafting artificial environments conducive to restoration. This approach aids in dissecting the positive and negative elements of the surroundings, thereby unveiling the abstract environmental quality. These abstract attributes provide designers with a more diverse range of methods for implementing attention restoration theories, beyond merely incorporating greenery into interior spaces.

This study seeks to enhance the connection between individuals and the urban environment, addressing the growing health concerns through an analysis of attention restoration research processes and trends. Using the core databases of Web of Science, PubMed, Google Scholar, and PsycINFO, and knowledge graph software such as CiteSpace5.8.R3, this paper presents a quantitative analysis of the pertinent literature. The research indicates that attention restoration studies have garnered significant interest from scholars globally. Nevertheless, numerous studies on attention restoration have yet to be translated into practical applications, presenting ongoing challenges that require further investigation and resolution.

## 2. Methodology

### *2.1. Data Collection*

The Web of Science, PubMed, Google Scholar, and PsycINFO databases are recognized for their comprehensive coverage of academic literature spanning various disciplines, providing researchers with access to a diverse range of attention recovery studies across different fields. This ensures a thorough representation of the current literature. A knowledge graph facilitates quantitative analysis by visually representing relationships and connections among studies. Its visualization capabilities track trends and the evolution of attention recovery research, providing a longitudinal perspective that ensures retrospectives capture not only the current state of the field, but also its historical development, including co-occurrence of research disciplines, publication trends, publication sources, keywords and their evolution trends, main authors, and frequently cited literature. Then, the literature analysis function is used to determine the research context and knowledge basis in this field. The key nodes and hot trends of attention recovery design are explored using a knowledge graph. Based on the analysis of the knowledge graph and the sorting of key knowledge contexts, the empirical research, research field, development process, and trend of attention recovery are identified and summarized.

### *2.2. Research Framework*

The basic data of this paper come from the Web of Science, PubMed, Google Scholar, and PsycINFO core collection databases. By comparing the results several times and by trial and error, the Topic = ("restorative environment" OR "stress recovery" OR "attention recovery" OR "perceived recovery") AND (environment OR architecture OR building OR urban). As a result, 5841 articles were screened, and the obtained literature was screened for intensive reading: ① papers of literature type selection, conference proceedings, and review papers; and ② citation frequency is higher or citation centrality is higher than 0.1. Some literature with a weak correlation was removed, and 571 kinds of literature were screened for analysis. Based on this, the mechanism of ART and research development trend involved in the selected literature were analyzed in the next step. The analysis and retrieval tools of the database, along with knowledge graph software, were utilized to analyze 571 literature records. The research conceptual model is shown in Figure 1.

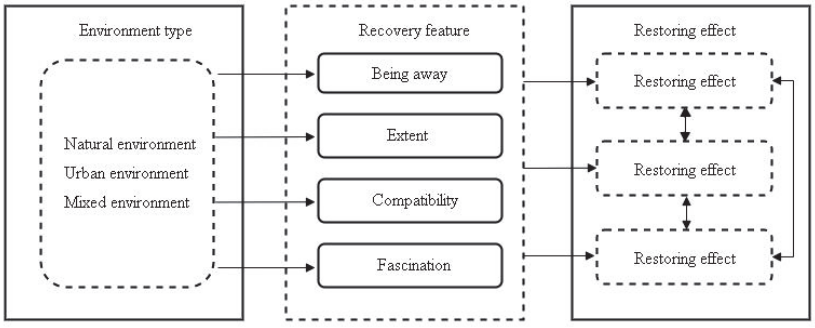



**Figure 1.** The study's conceptual model.

## 3. Results

### *3.1. Quantitative Analysis*

#### 3.1.1. Research Subject Co-Occurrence Analysis

Statistics show that ART covers a wide range of research directions in the database. The main disciplines are "Environmental Sciences", "Environmental Studies", "Ecology", "Social Science", and "Psychology". These have been major areas of attention recovery research for the last decade. These research directions have gradually expanded to such disciplines as Public Administration, Urban Studies, Engineering, Computer Science, and Business. Various research fields are integrated, and there is a strong correlation among research disciplines (Figure 2).

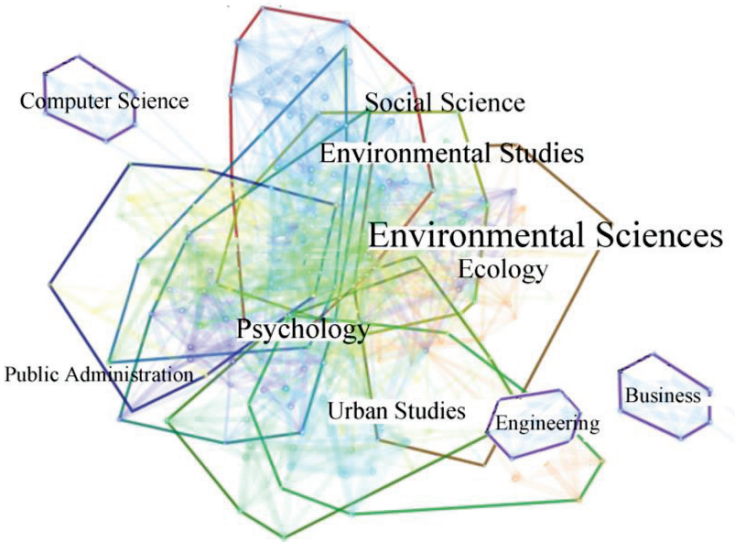



**Figure 2.** Co-occurrence analysis of research disciplines.

#### 3.1.2. Analysis of Publication Trends and Publication Sources

According to the statistical analysis of 5841 studies found in the databases and 571 studies screened and processed by the year of publication, it can be found that the number of relevant studies has shown an increasing trend in the past ten years (Figure 3), this means that the concept of health is receiving increasing attention nowadays. The design of comfort and livability of the space environment is also paid more attention by the public.

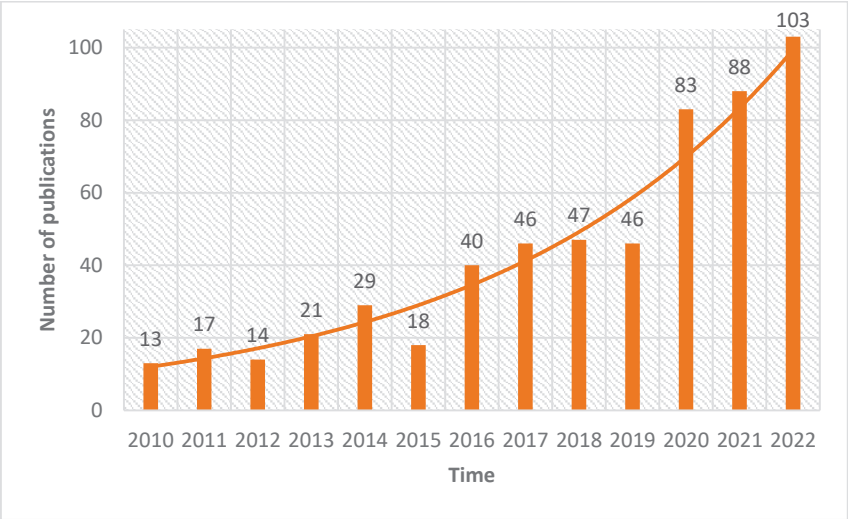



**Figure 3.** Trends of attention recovery studies published in the past decade.

Through the statistical analysis of literature sources with the tools of the database, it is found that *International Journal of Environmental Research and Public Health* published the most papers. *Frontiers in Psychology*, *Urban Forestry Urban Greening*, *Sustainability*, *Journal of Environmental Psychology*, and other journals followed. It can be seen that in recent years, public environmental health, psychology, urban green space, sustainability, and other relevant journal topics have paid more attention to the study of attention restoration design.

### 3.1.3. Keyword Atlas Analysis

A total of 571 literature records were imported into the knowledge graph software, and the software was run as a "keyword" node, corresponding to Descriptors and Identifiers in Web of Science, PubMed, Google Scholar, and PsycINFO database records. The threshold was set to 20, Timespan was set to 2010–2022, and the time slice was set to 1. The time slice selected the top 50 studies of each time slice, and node N = 186 was finally obtained, among which the topics that appeared more than 100 times were benefit, environment, stress, exposure, preference, and health. Finally, the line E = 1061 was obtained, indicating that there are more cross-studies among various topics and a strong correlation. With the gradual deepening of the research, the main keywords with high frequency gradually expanded to other related topics. Examples include "environmental psychology", "biophilic design", "directed attention", "nature exposure", and "health benefits" Keywords such as "benefit", "perceived restorative", and "SRT" continued to be the focus of research in 2019–2022 (Figure 4). Subject words with node N > 20 were selected, classified, and summarized in terms of the three directions of effect subject, effect object, and effect mechanism (Table 2). Among them, nodes with centrality greater than 0.1 are called key nodes. There were four key nodes: Attention, Response, Environment, and Landscape. In summary, the research showcases the evolution of the literature and research trends in the specified field, highlighting key topics, their interconnections, and the depth of investigation. It also suggests a continuous focus on certain core keywords alongside the emergence of new and related topics.

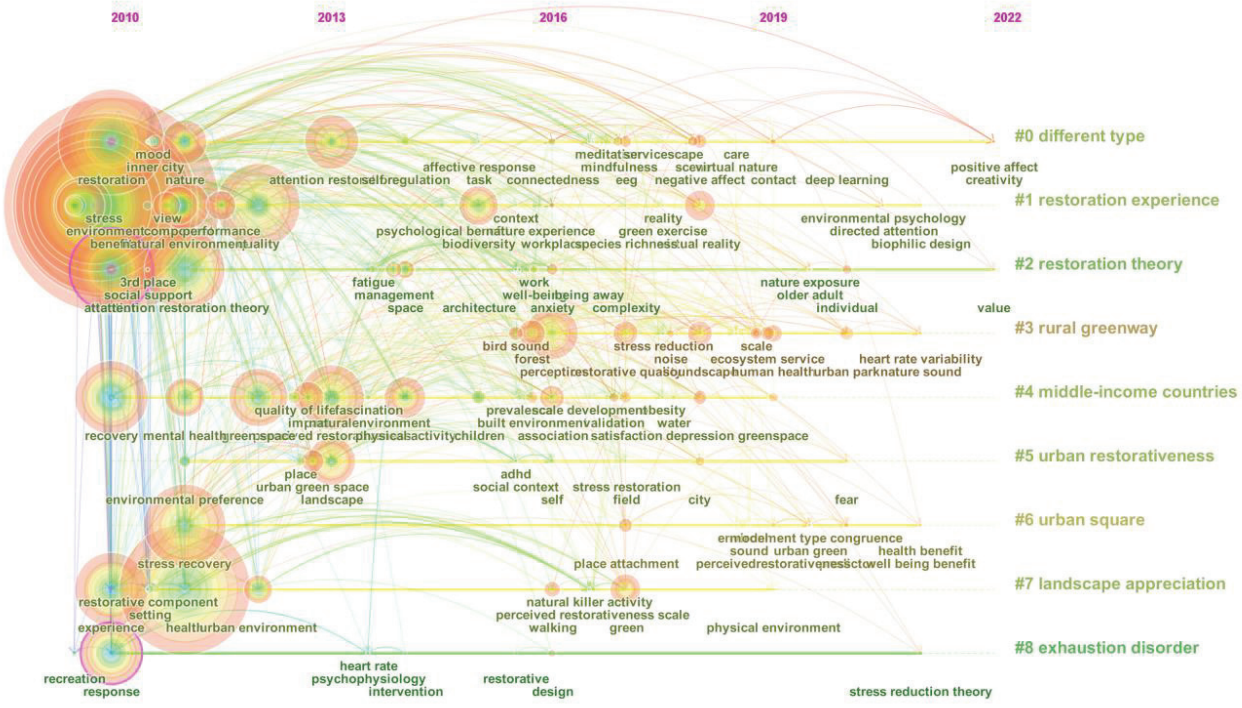



**Figure 4.** Timeline of keyword and cluster analysis.

**Table 2.** Clustering analysis of keywords in attention recovery based on node N > 20 in the CiteSpace5.8.R3 computing network.

| Effect Object | | | Effector | | | Effect Mechanism | | |
|---|---|---|---|---|---|---|---|---|
| **Subject Word** | **Total** | **Centrality** | **Subject Word** | **Total** | **Centrality** | **Subject Word** | **Total** | **Centrality** |
| Stress | 142 | 0.03 | Environment | 149 | 0.1 | Benefit | 174 | 0.09 |
| Preference | 108 | 0.08 | Restorative Environment | 99 | 0.06 | Exposure | 121 | 0.09 |
| Health | 106 | 0.08 | Green Space | 48 | 0.09 | Restoration | 90 | 0.06 |
| Attention | 74 | 0.17 | Urban | 44 | 0.02 | Stress Recovery | 69 | 0.07 |
| Response | 54 | 0.12 | Natural Environment | 42 | 0.05 | Experience | 60 | 0.08 |
| Perception | 42 | 0.05 | Landscape | 42 | 0.1 | Perceived Restorativeness | 56 | 0.06 |

#### 3.1.4. Knowledge Base Analysis

Applying the database, this research systematically selected and integrated literature based on relevance and citation frequency. Subsequently, this research compiled a list of ten highly cited papers in the field of attention recovery from international sources, each of which was cited more than 100 times in the past decade. These papers serve as crucial theoretical references for studies related to attention recovery (Table 3). Analyzing recent literature and findings from relevant authors in the past decade reveals a consistent focus on specific types of natural environments. The balance between artificial intervention in natural environments and entirely wild environments is approximately 1:1. Nevertheless, there is limited research on urban environments. Exposure durations for environmental testing vary significantly, typically spanning from 1 min to 4 h, with 10–15 min being the most prevalent duration. SRT proposes that exposure to certain natural environments can mitigate the physical, psychological, and behavioral effects of stressors. However, the majority of articles do not incorporate stressors in their studies. In the limited studies that incorporated stressors, these stressors encompassed cognitive tests conducted by Brown (2013) and Hartig (2003) [8,9], mild electric shocks administered by Hedblom et al. (2019) [10], arithmetic tests employed by Valtchanov and Ellard (2010), and the organization of stressful film clip viewings by Park et al. (2020) [11,12]. Notably, Sonntag et al. (2014) did not introduce stressors but instead focused on subjects from high-stress groups [13].

The literature cited in these studies collectively underscores the profound influence of natural experiences on human mental health and cognitive function. These studies offer valuable interdisciplinary and experimental insights, emphasizing the restorative attributes of nature, the potential influence of sound, and the necessity to investigate natural environments with attention-restoring qualities. Furthermore, these studies stressed the significance of a robust theoretical framework and research methodologies in attention recovery research, furnishing a fundamental theoretical foundation and reference for future investigations. Although the current research is dispersed across various fields, including psychology, engineering, physiology, medicine, and environmental science, concentrating on the overarching theme of this emerging field, rather than delving into specific details, facilitates the integration of research content. Moreover, a balance between theoretical and empirical research should be achieved, but currently there exists no model or framework to guide the development of measures or methods for creating restorative natural environments. Furthermore, it is crucial to strike a balance between theoretical and empirical research. However, currently, there is a lack of a comprehensive model or framework to guide developing measures or strategies for creating restorative natural environments.

**Table 3.** Hot literature on attention recovery in the past decade.

| Author | Publication Time | Cited Frequency | Article Title | Research Content |
|---|---|---|---|---|
| Markevych | 2017 | 866 | Exploring pathways linking greenspace to health: Theoretical and methodological guidance | The paper explores the interdisciplinary evidence linking green spaces to health. |
| Keniger, L.E. | 2013 | 556 | What are the Benefits of Interacting with Nature? | The study constructs new typologies of human–nature experiences and employs them to assess the benefits of human–nature interaction. |
| Bratman, G.N. | 2012 | 526 | The impacts of nature's experience on human cognitive function and mental health | The synthesis of multiple disciplines outlines how exposure to nature and an individual's preference for nature may influence the impact of the environment on mental functioning. |
| Tyrvainen, L. | 2014 | 499 | The influence of urban green environments on stress relief measures: A field experiment | The paper experimentally investigated the psychological and physiological effects of short-term visits to urban natural environments. |
| Bratman, G.N. | 2019 | 461 | Nature and mental health: An ecosystem service perspective | The paper extends the assessment of ecosystem services to mental health and proposes a heuristic conceptual model for this purpose. |
| Berman, M.G. | 2012 | 389 | Interacting with nature improves cognition and affects individuals with depression | The study experimentally investigated the benefits of nature walks in patients with major depressive disorder (MDD). |
| Carrus, G. | 2015 | 387 | Go greener, feel better? The positive effects of biodiversity on the well-being of individuals visiting, urban and peri-urban green areas | Field studies assessed the benefits and subjective well-being of urban residents accessing four different types of green space. |
| Ohly, H. | 2016 | 260 | Attention Restoration Theory: A systematic review of the attention restoration potential of exposure to natural environments | The study experimentally explores the mechanism of environmental restorative experience. |
| Ratcliffe, E. | 2013 | 204 | Bird sounds and their contributions to perceived attention restoration and stress recovery | The study found a relationship between bird calls, the most common type of sound in nature, and attention recovery. |
| Van den Berg, A.E. | 2014 | 193 | Evaluating restoration in urban green spaces: Does setting type make a difference? | The study examines the storability of urban public spaces with varying degrees of greening. The results indicate that the restoration of urban public spaces depends on individuals' perceived needs and the physical characteristics of the environment. |

### *3.2. Qualitative Analysis*

#### 3.2.1. Summary of Empirical Research Based on Quantitative Analysis

Through meta-analysis of the existing research literature, it can be seen that most researchers have quantified individual psychological and physiological indicators with the help of empirical research methods, including the observation method, conversation method, test method, experiment method, and case method. Experimental sites are divided into the laboratory and field. The test groups include college students, high school students, children, ordinary adults, and patients. The content of the test includes people's psychological reactions, physiological reactions, and cognitive performance [12].

(1) Research Methods and Steps

Experimental methods are commonly employed in attention recovery studies because they allow researchers to control for unrelated variables in a specific environment. This control is essential for investigating the intricate mental processes involved in attention recovery. Researchers frequently utilize experimental methods to intentionally expose

subjects to specific stimuli in a highly controlled environment, eliciting psychological and physiological responses. Following the presentation of the stimulus, researchers analyze the subjects' responses through direct observation, face-to-face conversations, and comprehensive questionnaire tests. Previous studies predominantly employed experimental methods in laboratory settings, conducting randomized controlled experiments to generate empirical data for attention recovery research. Experimental stimuli encompassed sound, analog images, and videos. Emfield and Neider conducted a study in which participants completed a battery of stress tests. Subsequently, participants were exposed to images of a designated environment as part of a restorative experiment. Finally, cognitive tests were administered to assess the recovery effects. Some of these studies incorporated sound variables alongside visual stimuli [13]. Evensen et al. investigated the restorative effects of various environmental settings on subjects using window views [14]. Some studies were conducted in real-world outdoor environments. For instance, in 2015, Bratman et al. investigated the attention-restoring effects of nature by observing how subjects interacted with natural settings, such as walking or jogging in natural surroundings [15]. Some studies also employ a case study approach, aiming to investigate and comprehend the long-term psychological changes in the test group. For instance, in 2015, Pilotti et al. conducted a video-based study on the environmental restorative effects of the test subjects. They also carried out a prolonged follow-up to enhance experimental accuracy [16]. In the current era of rapid technological development, virtual natural environments emerge as a potential solution. The experimental conditions and scenarios in virtual environments have become crucial for studying attention recovery in recent years. Researchers can precisely manipulate variables as needed, making this approach suitable for investigating attention recovery in various fields, including urban planning, medical facilities, and educational environments.

(2) Classification of Environment Types

Various studies encompass different environmental types, which can be broadly categorized into three groups: natural environments, urban environments, and mixed environments. In the realm of psychological research, these distinct environmental types exhibit varying impacts on attention recovery. The majority of studies delve into these three main environmental categories to investigate their differential roles in regulating attention recovery. Research consistently indicates that natural environments are generally deemed to be more restorative, and contact with such environments is beneficial for human health and well-being. Beyond the direct influence of environmental quality, the natural environment contributes positively, primarily by enhancing stress and emotional regulation [17]. Being in nature also yields favorable effects on physiological responses, including blood pressure, heart rate, skin conductivity, muscle tone, and cortisol levels [18]. Additionally, a multitude of studies have demonstrated that landscapes incorporating natural elements as stimuli are more restorative compared to those featuring artificial elements [19]. Consequently, many scholars employ natural environments as exemplars of restorative settings in their research. For instance, Beute (2014) examined the impact of nature on attention recovery through empirical research, while Bowler (2010) and Bratman (2015) investigated the positive effects of green spaces on mood enhancement and cognitive function improvement [16,20–22].

Urban environments, characterized by busy streets, crowded spaces, and tall buildings, often harbor potential stress-inducing factors when compared to natural surroundings. While urban environments may not offer the same level of restoration as natural settings, they do provide unique aesthetic experiences that can capture a portion of one's attention. Some researchers have even discovered that attention can be captivated by artificial objects that exhibit visual properties resembling those found in nature. Substituting a natural object with an artificial one possessing similar properties (e.g., color, shape, sound, etc.) can produce a comparable restorative effect [23]. Thus, creating a restorative built environment entails incorporating elements with natural qualities. These natural qualities in a space are not merely achieved through nature simulation but can also involve providing analogous properties (such as structural complexity and cohesion) abstractly to simulate nature,

thereby promoting stress relief. Understanding these principles is paramount in designing restorative urban environments. In recent years, an increasing number of scholars have shifted their research focus from natural environments to urban settings. For instance, Lyu (2022) examined the spatial characteristics within workplaces conducive to enhancing employee work efficiency and mental health [24]. Jeon (2021) explored the potential restorative effects of urban soundscapes [25]. Furthermore, Sonntag et al. (2014) conducted experimental research investigating the disparities in the impact of urban and natural environments on visitors' attention levels and physiological responses [13].

A hybrid environment combines elements of both natural and urban settings, such as a city park or a view that blends both aspects. Research indicates that such mixed environments also exhibit a degree of restorative potential, attributed to the diverse composition of these spaces, which enhances their visual appeal. This heightened attraction contributes to memorable and pleasurable experiences, fostering creativity and cognitive abilities. The richness of content within mixed environments can elevate individuals' sense of pride and belonging, consequently reducing stress levels and improving mood. For instance, studies conducted by Evensen (2015) explored the restoration effects of window views within mixed environments [15,26]. These investigations offer valuable insights into the incorporation of natural elements into urban landscapes to enhance human well-being.

(3) Evolution of Measurement Methods

The most common tool for assessing the restorative potential of the environment is the Perceptual Recovery Scale or its variants. The restorative impact of the environment on an individual can be gauged using psychological questionnaire scales. Hartig and Korpela, among others, initially developed the Perceptual Recovery Scale, which was subsequently modified by Herzog and Colleen. Each scale required participants to assess various dimensions based on their emotional responses to the environment. In their 2014 study, Van den Berg and Jorgensen utilized the self-rated Restorative Scale (RS), while Laumann in 2001 and Stevens in 2014 employed the Restorative Component Scale (RCS) [27–29]. The development and research details of the Perceptual Recovery Scale are presented in Table 4.

**Table 4.** Development and research contents of the Perceptual Recovery Scale.

| Theory | Author | Time | Content |
|---|---|---|---|
| PRICE | Hartig | 1997 | To measure the restorative nature of human-environment interaction, Hartig et al. developed the Perceptual Recovery Scale (PRS) to measure the quality of the restorative environment. |
| RCS | Laumann | 2001 | To make up for the shortcomings of PRS, Laumann et al. developed another set of environmental recovery component rating scales, which were named the Recovery Component Scale (RCS) in subsequent studies. |
| RS | Han K T | 2003 | Han K T et al. developed a reliable and effective self-assessment method for the quality of natural environment restoration, called the self-assessment Restoration Scale (RS). |
| PRCQ | Pals | 2009 | Pals et al. believe that zoos have restorative features in addition to natural environments. Based on PRS and RCS, they designed the Perceptual Restorative Feature Scale (PRCQ) for five kinds of restorative features of zoo attractions. |
| PDRQ | Lehto | 2013 | From the perspective of tourists, based on the theory of attention recovery, a 30-item PDRQ was developed. |

Due to the subjectivity of psychological questionnaire scales, researchers have increasingly explored objective assessments of physiological indicators related to attention fatigue and recovery. Biologists have identified two divisions within the human autonomic nervous system (ANS): the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). Stress induces various changes in the human autonomic nervous system. Specifically, stress leads to an increase in sympathetic nervous system (SNS) activity and a decrease in parasympathetic nervous system (PNS) activity. Wearable physiological monitoring systems offer advantages over subjective reports, as they can overcome the limitations associated with subjectivity. Research outcomes frequently involve measuring physiological signals and stress-related indicators such as EEG, EMG, EDA, HR (heart rate),

RR (respiratory rate), HRV (heart rate variability), and BPR (blood pressure). The most frequently used measures include heart rate (HR) and blood pressure (BPR). Additionally, Kang et al. (2022) and Park et al. (2007) assessed cerebral blood flow [30,31]. Zeng et al. (2020) assessed oxygen concentrations before and after the experiment [32]. Kobayashi (2019) and Yu et al. (2018) evaluated salivary alpha-amylase levels [33,34]. Genole et al. (2016) assessed salivary testosterone levels [35]. Li et al. (2011) determined the concentrations of adrenaline and dopamine in urine [36]. Hassan et al. (2018) and Reeves et al. (2019) recorded EEG measurements in their studies [37,38]. Despite substantial variability in the measured variables, no significant differences were observed in the results. Blood pressure was the most frequently employed measure in this research, with approximately half of the previous literature studies utilizing it. Nevertheless, blood pressure has demonstrated low sensitivity, and a substantial body of research suggests that heart rate (HR), heart rate variability (HRV), and salivary cortisol are more appropriate for measuring physiological indicators in this context [39,40].

3.2.2. Analysis of Research Fields Based on Action Mechanism

The process of attention recovery can be defined as a multi-stage experience process, which starts with attention recovery to reduce negative emotions and increase a series of positive emotions [41]. The information provided by the environment can be divided into different types of stimuli according to people's feelings. Stimuli are defined as factors that can affect human organic activities [42]. Individuals can perceive the stimuli of the surrounding environment through basic perception such as vision, hearing, touch, and smell, and produce a series of physiological, psychological, and cognitive reactions [43]. The mechanism model is shown in Figure 5. Previous research fields mainly focus on psychological recovery, physiological recovery, and cognitive recovery [23,44].

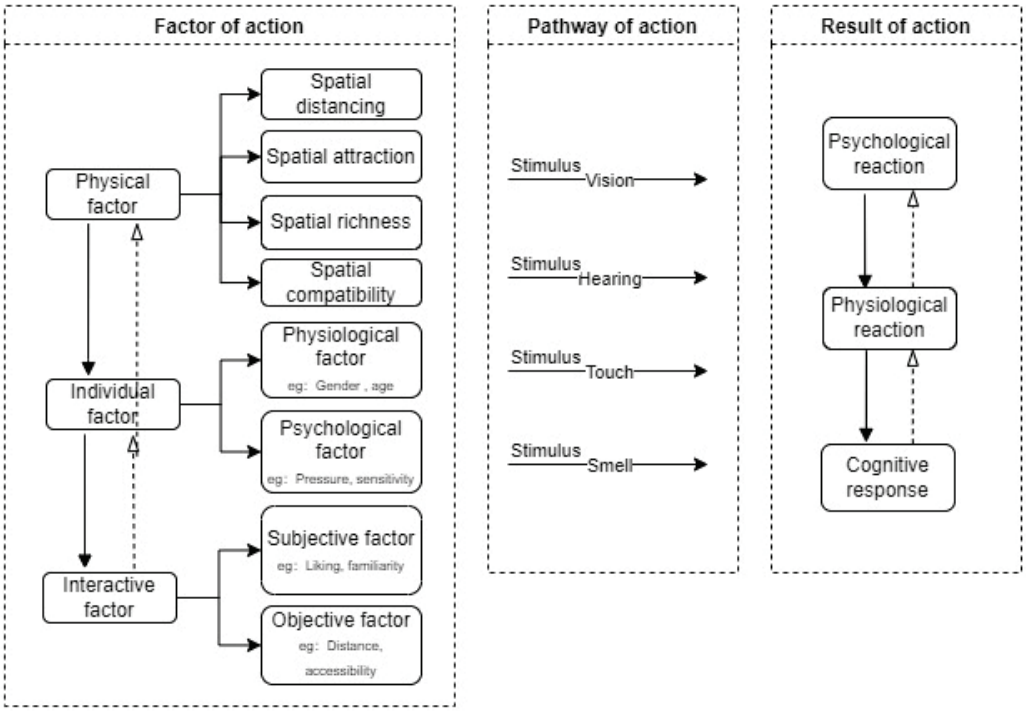



**Figure 5.** Mechanism model of attention recovery.

(1) Subjective Exploration of the Psychological Level

The keywords in psychological recovery research encompass terms such as "Stress", "Preference", "Restoration", "Psychological", and "Mental", among others. Typically, this research relies on psychological questionnaires to subjectively assess the psychological responses of participants. Psychological recovery studies have commonly explored both

directed and undirected attention [45]. Directed attention involves the intentional allocation of brain resources toward objects or areas linked to specific goals and tasks. Conversely, undirected attention is a cognitive resource that is spontaneously drawn toward salient stimuli without conscious control [42]. This study examines both attention consumption and recovery mechanisms, investigating how replenishing attention resources impacts psychological recovery. Research has demonstrated that prolonged directed attention can result in mental fatigue and, in severe cases, lead to significant mental health issues [7]. The restoration of attention resources leads to a reduction in negative emotions, providing individuals with a renewed sense of security and happiness. The restoration of attention resources can alleviate feelings of burnout, boredom, frustration, and anxiety, leading to positive changes that can benefit mental health [46]. In situations where individuals experience negative emotions due to stress, the environment can aid in reestablishing their focus and improving their mood, resembling a form of psychotherapy. For instance, intriguing and innovative spatial designs can offer individuals a sufficiently enriching spatial experience, allowing them a temporary respite from negative emotions. When the environmental conditions offer individuals a sufficient sense of security and comfort, their psychological state can relieve pressure through sensory healing and transition into the recovery stage.

(2) Objective Exploration on the Physiological Level

The key terms in physiological recovery research include "Health", "Exposure", "Experience", and "Association". This research typically builds upon psychological recovery and delves deeper into identifying physiological indicators for the objective assessment of attention fatigue and recovery. For instance, neuroimaging techniques like functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) are employed to monitor changes in cortical activation during attention recovery and to measure hormone concentrations, such as adrenaline, serotonin, and dopamine, which play roles in regulating attention recovery. Research indicates that attention restoration can reduce stress and fatigue, enhancing physical functioning [47]. This process can lower stress hormones, including heart rate, pulse rate, blood pressure, salivary cortisol, and adrenaline, alleviating physical stress. Additionally, it aids in balancing metabolism, decreasing the likelihood of heart disease, cardiovascular and cerebrovascular diseases, and other stress-related conditions [48]. Physiological and mental health are interconnected, influencing each other significantly. Positive mental health boosts the immune system, motivating physical activity and enhancing overall well-being [49]. Simultaneously, maintaining physical health is crucial for mental well-being.

(3) Validation Research on a Cognitive Level

Key terms in cognitive recovery research include "Attention", "Response", "Performance", and "Perception". Cognitive recovery is the most direct outcome of replenished attention resources. Researchers frequently assess task performance both before and after attention recovery. They also engage in long-term tracking and observation of cognitive behavior. Studies have shown that the relationship between attention recovery and cognitive ability lies in its support for work efficiency and sustainability. If attention resources are not supplemented in time, people may experience memory decline, slower reaction speed, increased error rate, etc., thus leading to a negative attitude towards cognitive tasks [50]. On the contrary, timely replenishment of attention resources can keep people's cognitive ability at an optimal level, and regular attention recovery is conducive to promoting sustainable utilization of cognitive resources, which is crucial for long-term and sustainable work [51]. The recovery of attention also has a series of positive knock-on effects, such as the ability to complete work tasks by providing continuous resources of attention, which in turn increases self-confidence and self-identity, and finally increases enthusiasm and motivation for work. In addition, innovation is a key skill in the knowledge age, and the process of innovation often requires a high degree of concentration. Abundant resources of directed attention are essential for those who engage in mental work for a long time [51].

3.2.3. Development Process and Trend Analysis Based on Research

(1) Review of the Development Process of Attention Recovery Research

Through a comprehensive review of the existing research literature and content, it is evident that the research process can be divided into three distinct stages (Figure 6):

① First Stage: Investigating Psychological and Physiological Recovery Mechanisms Guided by Attention Recovery.

In the initial research phase, scientists concentrated on the psychological and physiological mechanisms of attention recovery, crucial for comprehending the consumption and replenishment of attention resources. In this research phase, significant background and theoretical frameworks provide essential support. Kaplan's Attention Restoration Theory (1989) posits that exposure to natural environments promotes the recovery of directed attention, highlighting nature's role in replenishing attention resources and reducing mental fatigue [4]. Baumeister et al.'s Resource Exhaustion Theory (1998) asserts that self-control and concentration utilize limited cognitive resources, emphasizing the importance of recognizing these limitations in studying attention recovery [5]. Studies on neural mechanisms, including the utilization of techniques like functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) to monitor brain activity during attention recovery, have established a scientific foundation for this process [28]. During this stage, theoretical and empirical studies related to attention recovery mechanisms are particularly active. For instance, Kaplan (1995) delved into the mechanism of directed attention and its influence on emotional and cognitive performance, supported by existing experiments [5]. In 2013, Kirshbaum et al. conducted a study involving 25 patients experiencing moderate to severe fatigue [52]. This research, grounded in ART, employed non-pharmacological interventions aimed at alleviating the patients' illness-related discomfort. Ultimately, it offers valuable theoretical insights for the practical application of related research in clinical settings [52].

② Second Stage: Investigating the Impact of Various Environmental Types on Attention Recovery.

As research advanced, the focus shifted toward understanding the environmental influence on attention recovery. ART continues to be pivotal in this research stage, underscoring the influence of environmental factors [5]. Research in environmental psychology exploring how diverse environments (urban, natural, and mixed) impact human behavior and cognition offers a theoretical foundation for understanding the influence of environmental traits on attention recovery [30]. Researchers like Mark Berman have extensively investigated the impact of urban environments and persistent stressors on attention fatigue, highlighting the significance of bolstering environmental resilience [9]. At this stage, research predominantly centered on the interaction between various environmental types and attention restoration. For instance, Kaylin Adamson (2018) investigated the impact of different plant variables in office spaces on cognitive performance [53]. In a 2018 experiment, Jason investigated the influence of natural elements and auditory stimuli on individuals' attention recovery [54]. This exploration involved various sets of independent variables, such as combinations of natural photos with natural sounds, natural photos with classical music, and natural photos with classical music along with city scenes.

③ Third Stage: Practical Application in Different Contexts

In recent years, advancements in psychology, clinical medicine, and related disciplines have revealed that attention's restorative impact varies significantly across the human lifespan. Additionally, different social groups experience varying recovery intensities influenced by their unique factors. Distinct attention consumption patterns and recovery needs emerge among children, adolescents, adults, and the elderly due to physiological, cognitive, and experiential differences [38]. Practical research in fields like architecture, planning, and clinical psychology has increasingly focused on diverse groups, laying the theoretical groundwork for further attention recovery applications. This shift has led to attention to recovery studies exploring practical implications for different demographics. Notably, scholars such as Farhan Asim and Venu Shree integrated ART with biological principles in 2019 [55]. Their work delved into the relationship between psychological

recovery and nature, examining the influence and importance of various built environments in student dormitories on psychological recovery. Similarly, in 2012, Judith investigated design strategies aiming to enhance workplace happiness and attention levels, drawing from the biophile design theory and attention recovery concepts [56].

Overall, attention recovery research across the three stages mentioned has established a solid theoretical foundation, offering valuable guidance for advancing and refining relevant theories. However, the existing research accumulation still presents certain gaps, limiting its applicability in design practices. Notably, restorative environment theory has predominantly focused on outdoor landscapes, with limited application in indoor environment design. Consequently, there is a pressing need for research on attention restoration in artificial settings. The ultimate aim of this field is to translate fundamental attention restoration research into practical architectural design applications. This approach can reshape research content patterns and drive the future development of human-centered building environments.

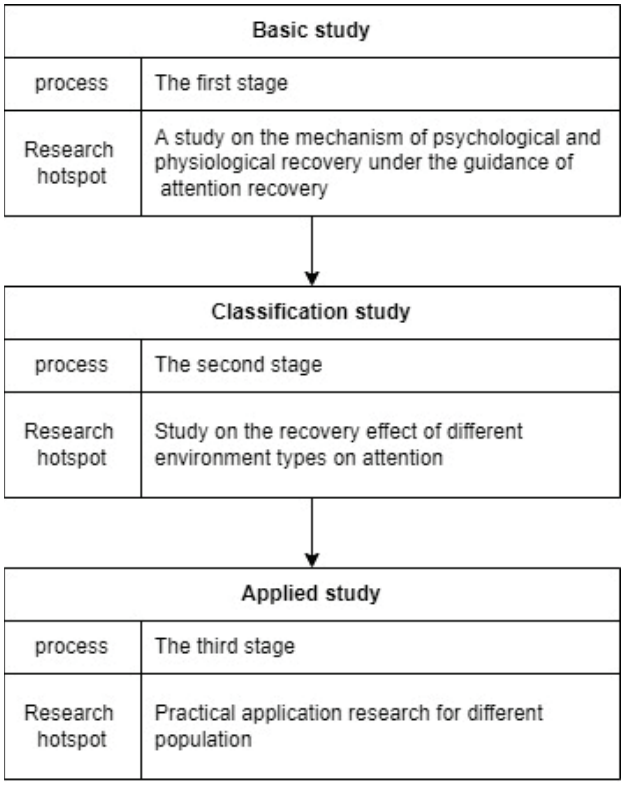



**Figure 6.** Research process diagram.

(2) Trends in Attention Restoration Research

① Analysis method: From quantitative analysis to the combination of quantitative and qualitative analysis

In the early literature, research often integrated multiple disciplines such as environmental science, psychology, and sociology. Based on the relevant theories of attention recovery, this study sets up various experimental scenes or controls different research independent variables to further study the promoting effect of environmental types and environmental elements on human attention recovery. Then, evidence is gathered through psychological questionnaire surveys and other ways, aiming at quantitative analysis of subjective feelings [57]. However, in recent years, more research has been based on quantitative analysis. The research combines literature analysis, case analysis, participation experience, and other non-quantitative means and methods, discusses and studies the problem from a theoretical perspective, and finally puts forward countermeasures and suggestions. For

example, Ming Lu explored the design strategy of a restorative campus based on students' perceived preferences in 2019 [58].

② Research subjects: The transition from the natural environment to the urban environment

In the early stage of research, scholars often regarded the natural environment and the urban environment as two kinds of opposite environments. The main purpose was to investigate the advantages of the natural environment over the urban environment in promoting mental health [59]. As the study progressed, the researchers discovered how difficult it was to create an entirely natural environment in a highly urbanized area. Resilience is not only a special property of the natural environment but also a spatial property. Beautifully designed and attractive built environments have restoration benefits similar to those of natural environments. Therefore, the main research direction is to integrate the natural environment into planning and design with the artificial environment as the carrier, and finally create an acquired restorative environment [2]. Therefore, scholars began to explore the restorative space design of different building types, such as residential buildings, office buildings, schools, and hospitals, based on the previous theoretical basis. For example, Smith studied and discussed the design of an open office based on the ART and biophile theory in 2013 [60]. In The Green Office, Elzinga studied and discussed the effect of office plants on relieving mental fatigue and stress [61].

③ Limiting factors: From the overall environment to a single environmental element

Most of the research is based on the influence of the overall natural environment or artificial environment on human physical and mental health because the early research is limited by the knowledge background. With further research, scholars began to study how individual environmental factors affect human psychological perception. These environmental elements include cultural background, visual arts, window views, space openness, interior landscape, color design, sound design, and interior environmental quality. For example, Myers studied the restorative effects of visual arts and place culture in 2020 [62]. Evensen analyzed the influence of windowless landscape elements on computer workers in 2015 [15]. Adamson explored the promoting effect of indoor landscape on individual cognitive performance in 2019 [53]. In 2020, Amirbeiki studied the influence of exposure to natural blue elements on the psychological recovery of college students [63]. Ratcliffe studied the restorative effect of sound production in 2021 [64]. Shengxian Kang studied the influence of indoor environment quality on the work efficiency of open scientific research office spaces in 2017 [65].

## 4. Conclusions

In recent years, attention recovery research has gained significant attention from scholars globally, with the body of related studies growing year by year. The fundamental characteristics of restorative environments offer a theoretical foundation for creating artificial environments with restorative qualities. Strategically applying attention restoration theory (ART) can address issues related to excessive stress and low work efficiency in society. Numerous studies have highlighted the advantages of implementing attention recovery theories in architecture. However, a thorough analysis of the knowledge landscape reveals that many studies of attention recovery have not yet translated into practical applications, and certain challenges require further investigation and resolution:

(1) Standardized Guidelines: The development of standardized guidelines for applying attention restoration theory (ART) in architectural practice could help overcome the inherent subjectivity of design strategies. These guidelines should consider diverse cultural backgrounds and empirical evidence to ensure their applicability across various contexts.
(2) Real-World Studies: While laboratory studies provide valuable insights, efforts should be made to conduct research in real-world environments to better understand the impact of attention recovery interventions. Researchers should strive to replicate

natural settings and conditions as closely as possible to improve the validity and relevance of findings.

(3) Diverse Sample Populations: To enhance the generalizability of research findings, future studies should prioritize diverse sample populations. This includes individuals from different age groups, cultural backgrounds, occupations, and lifestyles to capture a broader range of cognitive responses and experiences.

(4) Multi-Sensory Stimulation: Expanding the scope of research to include multi-sensory stimulation can enrich individuals' experiences and enhance attention recovery outcomes. Researchers should explore the potential of auditory, tactile, and olfactory stimuli in addition to visual stimuli to create more holistic and effective interventions.

(5) Interdisciplinary Collaboration: Encouraging interdisciplinary collaboration between psychologists, architects, urban planners, and other stakeholders can foster innovation and holistic approaches to addressing attention recovery challenges. By leveraging diverse expertise and perspectives, comprehensive solutions can be developed to enhance the restorative qualities of built environments.

By implementing these solutions, researchers can overcome existing challenges and advance the practical application of attention recovery theories, ultimately contributing to the creation of healthier and more supportive environments for individuals.

**Author Contributions:** Conceptualization, Y.Y.; methodology, C.L.; formal analysis, Y.Y.; writing—original draft, Y.L.; writing—review & editing, C.L., J.Z. and Y.Y.; funding acquisition, J.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China grant number 51578326 and the Natural Science Foundation of Shandong Province grant number ZR2023ME220 and the APC was funded by Yang Yang.

**Institutional Review Board Statement:** Ethical review and approval were waived for this study due to the ethical review and approval were waived for this study due to the use of anonymous surveys and absence of sensitive information or personal identifiers.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author due to confidentiality agreements with participants/subjects.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Wang, S. *Research on Design Strategy of University Campus Space Environment in Cold Regions with Attention Restoration Goal*; Harbin Institute of Technology: Harbin, China, 2020.
2. Ulrich, R.S.; Simons, R.F.; Losito, B.D.; Fiorito, E.; Miles, M.A.; Zelson, M. Stress recovery during exposure to natural and urban environments. *J. Environ. Psychol.* **1991**, *11*, 201–230. [CrossRef]
3. Yin, J.; Yuan, J.; Arfaei, N.; Catalano, P.J.; Allen, J.G.; Spengler, J.D. Effects of the biophilic indoor environment on stress and anxiety recovery: A between-subjects experiment in virtual reality. *Environ. Int.* **2019**, *136*, 105427. [CrossRef]
4. Kaplan, R.; Kaplan, S. *The Experience of Nature: A Psychological Perspective*; Cambridge University Press: Cambridge, UK, 1989.
5. Kaplan, S. The restorative benefits of nature: Toward an integrative framework. *J. Environ. Psychol.* **1995**, *15*, 169–182. [CrossRef]
6. Korpela, K.M.; Klemettilä, T.; Hietanen, J.K. Evidence for rapid affective evaluation of environmental scenes. *Environ. Behav.* **2002**, *34*, 634–650. [CrossRef]
7. Berto, R. The role of nature in coping with psycho-physiological stress: A literature review on restorativeness. *Behav. Sci.* **2014**, *4*, 394–409. [CrossRef] [PubMed]
8. Brown, D.K.; Barton, J.L.; Gladwell, V.F. Viewing nature scenes positively affects recovery of autonomic function following acute-mental stress. *Environ. Sci. Technol.* **2013**, *47*, 5562–5569. [CrossRef] [PubMed]
9. Hartig, T.; Evans, G.W.; Jamner, L.D.; Davis, D.S.; Garling, T. Tracking restoration in natural and urban field settings. *J. Environ. Psychol.* **2003**, *23*, 109–123. [CrossRef]
10. Hedblom, M.; Gunnarsson, B.; Iravani, B.; Knez, I.; Schaefer, M.; Thorsson, P.; Lundstrom, J.N. Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Sci. Rep.* **2019**, *9*, 10113. [CrossRef] [PubMed]
11. Valtchanov, D.; Ellard, C. Physiological and affective responses to immersion in virtual reality: Effects of nature and urban settings. *J. Cyber Ther. Rehabil.* **2010**, *3*, 359–373.

12. Park, B.J.; Tsunetsugu, Y.; Kasetani, T.; Kagawa, T.; Miyazaki, Y. The physiological effects of Shinrin-yoku (taking in the forest atmosphere or forest bathing): Evidence from field experiments in 24 forests across Japan. *Environ. Health Prev. Med.* **2010**, *15*, 18–26. [CrossRef]
13. Sonntag-Ostrom, E.; Nordin, M.; Lundell, Y.; Dolling, A.; Wiklund, U.; Karlsson, M.; Carlberg, B.; Slunga Jarvholm, L. Restorative effects of visits to urban and forest environments in patients with exhaustion disorder. *Urban For. Urban Green.* **2014**, *13*, 344–354. [CrossRef]
14. Emfield, A.G.; Neider, M.B. Evaluating visual and auditory contributions to the cognitive restoration effect. *Front. Psychol.* **2014**, *5*, 548. [CrossRef] [PubMed]
15. Evensen, K.H.; Raanaas, R.K.; Hagerhall, C.M.; Johansson, M.; Patil, G.G. Restorative elements at the computer workstation: A comparison of live plants and inanimate objects with and without window view. *Environ. Behav.* **2015**, *47*, 288–303. [CrossRef]
16. Bratman, G.N.; Daily, G.C.; Levy, B.J.; Gross, J.J. The benefits of nature experience: Improved affect and cognition. *Landsc. Urban Plan.* **2015**, *138*, 41–50. [CrossRef]
17. Pilotti, M.; Klein, E.; Golem, D.; Piepenbrink, E.; Kaplan, K. Is Viewing a Nature Video After Work Restorative? Effects on Blood Pressure, Task Performance, and Long-Term Memory. *Environ. Behav.* **2015**, *47*, 947–969. [CrossRef]
18. Browning, M.H.; Saeidi-Rizi, F.; McAnirlin, O.; Yoon, H.; Pei, Y. The role of methodological choices in the effects of experimental exposure to simulated natural landscapes on human health and cognitive performance: A systematic review. *Environ. Behav.* **2020**, *53*, 0013916520906481. [CrossRef]
19. Horiuchi, M.; Endo, J.; Akatsuka, S.; Uno, T.; Hasegawa, T.; Seko, Y. Influence of forest walking on blood pressure, profile of mood States, and stress markers from the viewpoint of aging. *J. Aging Gerontol.* **2013**, *1*, 9–17. [CrossRef]
20. Tsunetsugu, Y.; Park, B.J.; Ishii, H.; Hirano, H.; Kagawa, T.; Miyazaki, Y. Physiological effects of Shinrin-yoku (taking in the atmosphere of the forest) in an old-growth broadleaf forest in Yamagata prefecture, Japan. *J. Physiol. Anthropol.* **2007**, *26*, 135–142. [CrossRef] [PubMed]
21. Beute, F.; De Kort, Y.A.W. Natural resistance: Exposure to nature and self-regulation, mood, and physiology after ego-depletion. *J. Environ. Psychol.* **2014**, *40*, 167–178. [CrossRef]
22. Bowler, D.E.; Buyung-Ali, L.; Knight, T.M.; Pullin, A.S. A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health* **2010**, *10*, 456. [CrossRef]
23. Ohly, H.; White, M.P.; Wheeler, B.W.; Bethel, A.; Ukoumunne, O.C.; Nikolaou, V.; Garside, R. Attention Restoration Theory: A systematic review of the attention restoration potential of exposure to natural environments. *J. Toxicol. Environ. Health Part B Crit. Rev.* **2016**, *19*, 305–343. [CrossRef] [PubMed]
24. Lyu, K.; de Dear, R.; Brambilla, A.; Globa, A. Restorative benefits of semi-outdoor environments at the workplace: Does the thermal realm matter? *Build. Environ.* **2022**, *222*, 109355. [CrossRef]
25. Jeon, J.Y.; Jo, H.I.; Lee, K. Potential restorative effects of urban soundscapes: Personality traits, temperament, and perceptions of VR urban environments. *Landsc. Urban Plan.* **2021**, *214*, 104188. [CrossRef]
26. Stevenson, M.P.; Schilhab, T.; Bentsen, P. Attention Restoration Theory II: A systematic review to clarify attention processes affected by exposure to natural environments. *J. Toxicol. Environ. Health Part B* **2018**, *21*, 227–268. [CrossRef] [PubMed]
27. Van den Berg, A.E.; Jorgensen, A.; Wilson, E.R. Evaluating restoration in urban green spaces: Does setting type make a difference? *Landsc. Urban Plan.* **2014**, *127*, 173–181. [CrossRef]
28. Laumann, K.; Gärling, T.; Stormark, K.M. Rating scale measures of restorative components of environments. *J. Environ. Psychol.* **2001**, *21*, 31–44. [CrossRef]
29. Stevens, P. Affective priming of perceived environmental restorativeness. *Int. J. Psychol.* **2014**, *49*, 51–55. [CrossRef] [PubMed]
30. Kang, M.; Kim, S.; Lee, J. Pilot study on the physio-psychological effects of botanical gardens on the prefrontal cortex activity in an adult male group. *J. People Plants Environ.* **2022**, *25*, 413–423. [CrossRef]
31. Park, B.J.; Tsunetsugu, Y.; Kasetani, T.; Hirano, H.; Kagawa, T.; Sato, M.; Miyazaki, Y. Physiological effects of Shinrin-yoku (taking in the atmosphere of the forest)–using salivary cortisol and cerebral activity as indicators. *J. Physiol. Anthropol.* **2007**, *26*, 123–128. [CrossRef]
32. Zeng, C.; Lyu, B.; Deng, S.; Yu, Y.; Li, N.; Lin, W.; Li, D.; Chen, Q. Benefits of a three-day bamboo forest therapy session on the physiological responses of university students. *Int. J. Environ. Res. Public Health* **2020**, *17*, 3238. [CrossRef]
33. Kobayashi, H.; Song, C.; Ikei, H.; Park, B.J.; Kagawa, T.; Miyazaki, Y. Combined effect of walking and forest environment on salivary cortisol concentration. *Front. Public Health* **2019**, *7*, 480661. [CrossRef] [PubMed]
34. Yu, C.P.; Lee, H.Y.; Luo, X.Y. The effect of virtual reality forest and urban environments on physiological and psychological responses. *Urban For. Urban Green.* **2018**, *35*, 106–114. [CrossRef]
35. Geniole, S.N.; David, J.P.F.; Euz'ebio, R.F.R.; Toledo, B.Z.S.; Neves, A.I.M.; McCormick, C.M. Restoring land and mind: The benefits of an outdoor walk on mood are enhanced in a naturalized landfill area relative to its neighboring urban area. *Ecopsychology* **2016**, *8*, 107–120. [CrossRef]
36. Li, Q.; Otsuka, T.; Kobayashi, M.; Wakayama, Y.; Inagaki, H.; Katsumata, M.; Hirata, Y.; Li, Y.; Hirata, K.; Shimizu, T.; et al. Acute effects of walking in forest environments on cardiovascular and metabolic parameters. *Eur. J. Appl. Physiol.* **2011**, *111*, 2845–2853. [CrossRef] [PubMed]

37. Hassan, A.; Tao, J.; Li, G.; Jiang, M.; Aii, L.; Zhihui, J.; Zongfang, L.; Qibing, C. Effects of walking in bamboo forest and city environments on brainwave activity in young adults. *Evid.-Based Complement. Altern. Med.* **2018**, *2018*, 9653857. [CrossRef] [PubMed]
38. Reeves, J.P.; Knight, A.T.; Strong, E.A.; Heng, V.; Neale, C.; Cromie, R.; Vercammen, A. The application of wearable technology to quantify health and wellbeing Co-benefits from urban wetlands. *Front. Psychol.* **2019**, *10*, 1840. [CrossRef] [PubMed]
39. Corazon, S.S.; Sidenius, U.; Poulsen, D.V.; Gramkow, M.C.; Stigsdotter, U.K. Psycho-physiological stress recovery in outdoor nature-based interventions: A systematic review of the past eight years of research. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1711. [CrossRef] [PubMed]
40. Kondo, M.C.; Jacoby, S.F.; South, E.C. Does spending time outdoors reduce stress? A review of real-time stress response to outdoor environments. *Health Place* **2018**, *51*, 136–150. [CrossRef]
41. Arnett, J.J. *The Neglected 95%: Why American Psychology Needs to Become Less American*; American Psychological Association: Washington, DC, USA, 2016.
42. Sedghikhanshir, A.; Zhu, Y.; Beck, M.R.; Jafari, A. The Impact of Visual Stimuli and Properties on Restorative Effect and Human Stress: A Literature Review. *Buildings* **2022**, *12*, 1781. [CrossRef]
43. Pinto, Y.; van der Leij, A.R.; Sligte, I.G.; Lamme, V.A.; Scholte, H.S. Bottom-up and top-down attention are independent. *J. Vis.* **2013**, *13*, 16. [CrossRef]
44. Menardo, E.; Brondino, M.; Hall, R.; Pasini, M. Restorativeness in natural and urban environments: A meta-analysis. *Psychol. Rep.* **2021**, *124*, 417–437. [CrossRef] [PubMed]
45. Folk, C.L.; Remington, R.W.; Johnston, J.C. Involuntary covert orienting is contingent on attentional control settings. *J. Exp. Psychol. Hum. Percept. Perform.* **1992**, *18*, 1030. [CrossRef] [PubMed]
46. Fandetti, R. *Attention Restoration Theory: Urban Versus Natural Stimuli Effects on Working Memory*; California State University: Long Beach, CA, USA, 2022.
47. Schumann, F.; Steinborn, M.B.; Kürten, J.; Cao, L.; Händel, B.F.; Huestegge, L. Restoration of attention by rest in a multitasking world: Theory, methodology, and empirical evidence. *Front. Psychol.* **2022**, *1415*, 867978. [CrossRef] [PubMed]
48. Ryan, C.O.; Browning, W.D.; Clancy, J.O.; Andrews, S.L.; Kallianpurkar, N.B. Biophilic design patterns: Emerging nature-based parameters for health and well-being in the built environment. *ArchNet-IJAR Int. J. Archit. Res.* **2014**, *8*, 62. [CrossRef]
49. Timm, S.; Dearborn, L.; Pomeroy, J. Nature and the City: Measuring the Attention Restoration Benefits of Singapore's Urban Vertical Greenery. *Technol. Archit. Des.* **2018**, *2*, 240–249. [CrossRef]
50. Stevenson, M.P.; Dewhurst, R.; Schilhab, T.; Bentsen, P. Cognitive restoration in children following exposure to nature: Evidence from the attention network task and mobile eye tracking. *Front. Psychol.* **2019**, *10*, 42. [CrossRef] [PubMed]
51. Korpela, K.; De Bloom, J.; Kinnunen, U. From restorative environments to restoration in work. *Intell. Build. Int.* **2015**, *7*, 215–223. [CrossRef]
52. Kirshbaum, M.N.; Donbavand, J. Making the most out of life: Exploring the contribution of attention restorative theory in developing a non-pharmacological intervention for fatigue. *Palliat. Support. Care* **2014**, *12*, 473–480. [CrossRef]
53. Adamson, K.; Thatcher, A. Do indoor plants improve performance outcomes?: Using the attention restoration theory. In *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018) Volume VIII: Ergonomics and Human Factors in Manufacturing, Agriculture, Building and Construction, Sustainable Development and Mining 20*; Springer International Publishing: Berlin/Heidelberg, Germany, 2019; pp. 591–604.
54. Boggs, J. *The Roles of Biophilic Attitudes and Auditory Stimuli within Attention Restoration Theory*; University of Nevada: Las Vegas, NV, USA, 2018.
55. Asim, F.; Shree, V. The impact of Biophilic Built Environment on Psychological Restoration within student hostels. *Vis. Sustain.* **2019**.
56. Green, J. Back to Nature for Good: Using Biophilic Design and Attention Restoration Theory to Improve Well-Being and Focus in the Workplace. Master's Thesis, University of Minnesota, Minneapolis, MN, USA, 2012.
57. Jaggard, C.E. *The Effect of Intentionally Engaging Attention when Viewing Restorative Environments: Exploring Attention Restoration Theory*; Indiana State University: Terre Haute, IN, USA, 2014.
58. Lu, M.; Fu, J. Attention restoration space on a university campus: Exploring restorative campus design based on environmental preferences of students. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2629. [CrossRef]
59. Yue, M.; Zhang, X.; Zhang, J. Analysis of knowledge graph of pro-nature building design and its health benefit. *South. Archit.* **2022**, *11*, 12–20.
60. Smith, L.E. Attention Restoration Theory and the Open Office: Addressing Mental Fatigue in Low Stimulus Screeners and Creative Class Workers through Biophilic Design. Master's Thesis, The Savannah College of Art and Design, Atlanta, GA, USA, 2013.
61. Elzinga, L.A.J. *The Green Office: The Influence of Plants at the Office, Effectuating a More Natural Environment, on Restoration from Mental Fatigue and Stress as Mediated by Restorative Characteristics among Office Employees*; University of Twente: Enschede, The Netherlands, 2020.
62. Myers, M.G. *Visual Art as a Restorative, Placed-Based Biophilic Coping Mechanism in the Workplace: A Case Study*; Kent State University: Kent, OH, USA, 2020.

63. Amirbeiki, F.; Khaki Ghasr, A. Investigating the Effects of Exposure to Natural Blue Elements on the Psychological Restoration of University Studentsity Students. *Iran Univ. Sci. Technol.* **2020**, *30*, 1–10.
64. Ratcliffe, E. Sound and soundscape in restorative natural environments: A narrative literature review. *Front. Psychol.* **2021**, *12*, 570563. [CrossRef]
65. Kang, S.; Ou, D.; Mak, C.M. The impact of indoor environmental quality on work productivity in university open-plan research offices. *Build. Environ.* **2017**, *124*, 78–89. [CrossRef]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

buildings

MDPI

*Article*

# Research on Optimization Strategy of Commercial Street Spatial Vitality Based on Pedestrian Trajectories

**Jinjiang Zhang [1], Wenyu Zhou [1], Haitao Lian [1,2,*] and Ranran Hu [1]**

[1] School of Architecture and Design, Hebei University of Engineering, Handan 056038, China; zhouwenyu0714@gmail.com (W.Z.)
[2] School of Architecture, Tianjin University, Tianjin 300072, China
* Correspondence: lianhaitao@hebeu.edu.cn

**Abstract:** Commercial pedestrian streets significantly enhance urban life. Previous research often depends on limited survey data or subjective evaluations, which fail to fully capture the impact of street elements on spatial vitality under diverse spatiotemporal conditions. This study, conducted in Beijing's Sanlitun commercial district, analyzes pedestrian data from six branch roads collected via WiFi detection to determine how various spatial elements influence the vibrancy of commercial pedestrian streets. The results show a positive correlation between street width, ranging from 5.88 to 10.83 m, and vitality. Furthermore, the influence of different street elements on vitality varies notably. During the daytime, street width is the most effective element for enhancing vitality, with a maximum standardized coefficient of 1.717. However, at night, the associations between advertising area, store type, and vitality diminish. The street recording the highest nighttime vitality peaked at a pedestrian count of 91.7831. The contribution of street width to enhancing nighttime vitality is 2.49 times greater than at noon on non-working days, 2.01 times more than on working days, and 2.92 times higher than the impact of tables and chairs. Therefore, street design should prioritize street width, ground floor interface permeability, number of tables and chairs, store density, advertising area, and store type.

**Keywords:** smart city; pedestrian participation; pedestrian trajectory; spatial vitality; street elements

**Citation:** Zhang, J.; Zhou, W.; Lian, H.; Hu, R. Research on Optimization Strategy of Commercial Street Spatial Vitality Based on Pedestrian Trajectories. *Buildings* **2024**, *14*, 1240. https://doi.org/10.3390/buildings14051240

Academic Editors: Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Baojie He and Shi Cheng

Received: 11 March 2024
Revised: 15 April 2024
Accepted: 24 April 2024
Published: 26 April 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

In recent decades, the phenomenon of "ghost streets" has emerged in cities such as Berlin, London, Detroit, and Shanghai [1]. These streets have experienced significantly lower development and utilization rates than expected, leading to an evident waste of urban space and attracting considerable attention [2]. To revitalize these areas, substantial investments in reconstruction are often necessary [3]. However, these plans do not always yield the anticipated success, making the enhancement of vitality within limited urban spaces a pressing topic in urban studies [4].

Additionally, many major cities across France, China, and Japan face the challenge of urban shrinkage, which has drained the original vitality from their streets, posing new challenges to economic and social development [5]. There is an urgent need for a method that can accurately predict and evaluate urban vitality based on proposed plans. Such a method would minimize risks prior to construction and provide crucial guidance for urban development.

During the inventory renewal period, research on urban spatial vitality has primarily focused on the macro-urban level, with fewer studies addressing the micro-level vitality of street spaces [6]. Yet, micro street spaces are intimately linked to residents' daily experiences [7]. As highly dynamic micro-urban environments, commercial pedestrian streets increasingly emphasize enhancing street vitality in their spatial renewal designs [8]. Recent empirical studies have demonstrated that the spatial form, functional attributes, and

facilities of streets [9] can attract activities, and optimizing street vitality is now recognized as a crucial strategy for improving spatial quality.

In existing research, spatial vitality often receives less attention in small-scale urban spaces and primarily depends on subjective evaluations and qualitative descriptions, lacking a robust measurement of impact weights [10]. Traditional methods, such as behavioral records, participant observation, questionnaires, and interviews, typically cover only limited time segments and smaller scales [11]. The introduction of pedestrian trajectory capture technology has enabled the collection of new data sources that facilitate the observation of street vitality over extended periods and at a broader scale while also providing detailed insights. This research advances a more refined quantitative analysis, elucidating the influence of the built environment on street vitality and quantifying the impact weights of different elements [12]. Additionally, by considering the distribution of spatiotemporal characteristics, this study has analyzed these elements' effects on the vitality of street space. Understanding the influence of spatial elements on the vitality of commercial pedestrian streets is crucial for designing commercial street spaces and enhancing the quality of street experiences.

This study begins with a literature review to identify elements that significantly impact pedestrian trajectories in commercial street spaces and to establish a method for calculating the spatial vitality of these trajectories. Secondly, six east–west branch streets in the Sanlitun Commercial District in Beijing, China, were selected to extract pedestrian trajectory data via WiFi detection. Thirdly, the spatial vitality values of these pedestrian trajectories were calculated, and regression analysis was conducted with the primary street element data to quantitatively assess the impact of street elements on spatial vitality. Finally, this study derived rules for the influence of spatial elements on the spatial vitality of commercial pedestrian streets and, based on these findings, proposed optimization strategies for commercial streets.

## 2. Literature Review

### *2.1. Vitality of Street Space*

The spatial vitality of street spaces relates to their potential for survival and development, assessable through two primary observational methods: macroscopic and microscopic. Some scholars, using cities as examples, employ multi-source data to measure urban vitality [13]. At the macro scale, significant attention is given to the vitality of street space, from employing the store density (SD) method to evaluate vitality based on human perception [14,15] to large-scale quantitative analyses that build frameworks for understanding the impact of street vitality and exploring factors influencing it [16]. Additionally, field surveys and open-source network data are utilized to construct a street vitality evaluation index for commercial districts [17]. At the micro scale, methods to study street vitality include using the midpoint of the street as an observation point to mitigate the effects of road intersections and other variables on pedestrian flow distribution [18]. By using location data to document the main distribution characteristics of pedestrians, it has been observed that the spatial facilities and functional layouts of streets mutually enhance each other, thus increasing their attractiveness to people [19]. Using location information to record the main distribution characteristics of pedestrians, it is found that the spatial facilities and functional layout of the block strengthen each other, accelerating the attraction of pedestrian flow [20]. To evaluate the impact of spatial elements on vitality, it is crucial to consider the activity characteristics of individuals at a microscopic level, including detailed spatial attributes. In commercial pedestrian streets, particular emphasis is placed on how the functional attributes of the street, spatial form, and facilities affect micro-individual activities [9,21]. Drawing from the literature, this study identifies key factors that significantly affect spatial vitality in the micro-spaces of commercial streets, such as store density [22], store types [23], ground floor interface permeability [24], pedestrian width [25], the number of public tables and chairs [26], and billboard area [27]. Leveraging established research methods, scholars continue to investigate the influence of street elements on spatial vitality.

Overall, relatively mature research on the vitality of commercial districts has been conducted at the macro level, but research on the vitality of commercial streets at the micro level still needs to be strengthened. In particular, research on the vitality of commercial streets that integrates three dimensions of crowd activity, spatial change, and temporal change is even rarer, and this research is crucial for deepening understanding of the operating mechanism of commercial street vitality and formulating scientific optimization strategies.

### *2.2. Pedestrian Trajectories*

Collecting pedestrian spatio-temporal information to represent vitality from a micro perspective remains a challenging task for effective vitality assessment. The primary challenge is to gather this information in an efficient manner that accurately reflects vitality. In existing research, methods such as actual measurements [28] and questionnaires [29] are predominantly used in micro-scale street environments. These methods involve processing pedestrian location information, which can be inaccurate, costly, and time-consuming. Conducting such studies on a large scale presents significant challenges. With the advent of big data, resources such as mobile phone signaling data [30], social media check-ins [31], and GPS data [32] have been utilized in spatial vitality research. While big data offer extensive coverage, long-term data collection, and low acquisition costs, its coarse granularity presents difficulties in conducting detailed spatial vitality research on micro-scale commercial pedestrian streets.

By reviewing existing research, this study aims to collect higher-precision pedestrian spatio-temporal information leveraging big data techniques. Hou utilized video datasets and computer vision techniques to record pedestrian trajectories and quantify the utilization of small public spaces [33], demonstrating that variations in the number of individuals at different times can serve as an indicator of street vitality. Williams et al. employed tracking algorithms to monitor the flow of people and generate social cohesion images [34], finding that crowd-gathering behavior varied across different functional types of street spaces. Yan et al. extracted pedestrian movement trajectories from videos [35] and analyzed the spatiotemporal distribution of stays, revealing that pedestrian stay times varied in street spaces with different interface forms. Li et al. used a multi-target tracking algorithm [26] to quantitatively assess vitality by analyzing pedestrian counts, confirming that the spatial form of streets directly impacts changes in spatial vitality. These approaches address the challenges of data collection inherent in traditional methods, overcome the limitations of non-visual big data, and enhance the level of detail and accuracy in capturing crowd dynamics.

Certain methodologies focus primarily on quantitatively analyzing location information across spatial and temporal dimensions while also incorporating qualitative discussions about human activities. A more advanced approach is that of Tong Niu, who captures pedestrian trajectory information from video data [36] and proposes a vitality quantification model through multiple linear regression analysis based on quantitative indicators. However, studies on the detailed spatial optimization design for commercial pedestrian streets, particularly based on pedestrian trajectories, have been relatively limited. Consequently, there is a lack of established general principles regarding the impact of spatial design parameters on the optimization of these streets. Specifically, studies that examine the combined impact of design parameters—such as store density, store type, ground floor interface permeability, street width, the number of public tables and chairs, and billboard area—on spatial optimization to accurately assess spatial vitality are scarce in the Chinese literature.

### *2.3. Behavior Mapping*

In addition, this study used a method of using video datasets to record pedestrian trajectories, and through this behavior mapping method, researchers can gain a deeper understanding of pedestrian activity patterns. However, the effectiveness and scientificity of this method still need to be rigorously validated. Sommer R. mentioned that behavior

mapping is a continuous process of collecting time and behavior data, which requires an observation schedule to systematically collect behavior data over a long period of time [37]. Robin C. Moore used visual methods to mark children's sites on the floor plan of community open spaces and found that different natural spatial features may affect children's physical activity levels [38]. Zordan M. collected data on crowd behavior mapping using visual snapshots and found that the underlying features of buildings can affect the density of human face-to-face interaction [39]. Villani C., on the other hand, places more emphasis on precise capture of spatiotemporal information. She has positioned different activity behaviors in the GIS environment and found that pedestrian streets, as public open spaces, are in intense conflict with the behavior of personal power due to their transportation and commercial nature [40]. In another article, it was proposed that migrant workers in Hong Kong, as a vulnerable social group, faced problems of human rights, space justice, and urban inclusiveness during COVID-19. This research method not only provides us with a deeper understanding of pedestrian behavior but also triggers thinking about urban planning and management [41]. Therefore, the use of video datasets to record pedestrian trajectories has brought new possibilities for urban research.

### *2.4. Concept Definition*

Street vitality is characterized primarily by spatial attributes, manifesting as the distribution patterns of human activity intensity on streets. These spatial characteristics are observed through the presence and activities of individuals within a specific spatial context. Moreover, street vitality encompasses temporal characteristics [42]. Jacobs posits that street vitality arises from the fluctuating flow of people at different times. Two key phenomena associated with street vitality are the absolute number of people utilizing city streets and their temporal distribution throughout the day [43], with an emphasis on the significance of time distribution. The assessment of street vitality involves quantifying various activities within the street space, such as counting the number of people staying, walking slowly, and participating in other activities. It also includes evaluating the distribution of these activities at different times of the day. The intensity of crowd activity on the street can be quantified by its spatiotemporal characteristics, which define the essence of street vitality.

### *2.5. Objective*

Against this backdrop, the objective of this study is to evaluate the spatial vitality of commercial pedestrian streets using the pedestrian trajectory method. The research aims to quantify the impact of design parameters on spatial vitality, specifically addressing three key issues:

(I) How do the design parameters of commercial pedestrian streets influence spatial vitality in terms of spatial characteristics?
(II) How do the design parameters affect spatial vitality in terms of temporal characteristics?
(III) Considering the dynamic changes in spatial and temporal characteristics, which design parameters should be prioritized in the planning of a commercial pedestrian street?

## 3. Methods

### *3.1. Research Framework*

This study investigates the influence of spatial elements on pedestrian trajectory behavior within commercial pedestrian streets. A street design optimization strategy, guided by the promotion of vitality, is proposed. The research content and steps are outlined in the following figure (Figure 1):

(I) Six street space samples with representative environmental characteristics were selected within the Sanlitun commercial district in Beijing, China.
(II) During the same time period, four specific time intervals were chosen to conduct WiFi trajectory data collection for these six samples. The collection process involved documenting various pedestrian trajectory behaviors and the spatial element configuration of each sample.

(III) For data analysis, trajectory behavior data were extracted according to specific analytical requirements. It is proposed that the data concerning factors and vitality be modeled using ordered logistic regression equations in SPSS. This evaluation will help ascertain the impact of various factors on street vitality under different pedestrian densities and aid in constructing a spatial configuration model for commercial pedestrian streets aimed at enhancing vitality.

(IV) In line with design requirements, priorities should be rationally allocated to propose street-type design methods tailored to different priority levels.

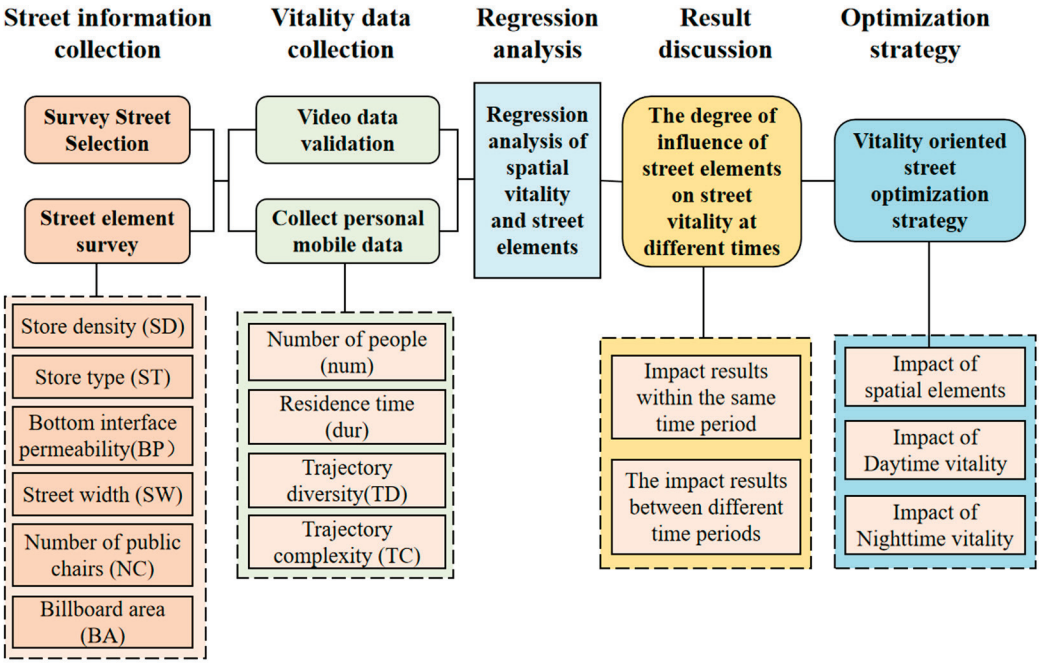



**Figure 1.** Workflow of holistic approach.

### *3.2. Sample Selection*

Beijing's Sanlitun Commercial Pedestrian Street has a large number of activities, obvious differences in vitality, and high application value [44]. This article uses six commercial pedestrian street spaces as sample spaces and conducts eight on-site surveys at Taikoo Li Sanlitun, four times on 20 August 2023 (Sunday) and four times on 21 August 2023 (Monday), each involving daytime hours, nights, working days, non-working days [45]. To analyze changes in the amount of positioning data and the number of external trust sources, each piece of data includes the device MAC address, collection timestamp, probe number, and distance between the device and the probe. Among them, device groups 1, 2, 3, 4, 5, and 6 in Sanlitun South District detect 6 east–west streets, as shown in Figure 2.

The data collected are the flow trajectory data of Sanlitun South District. The data collection times are 12:00–13:30, 14:00–15:30, 16:00–17:30, and 19:00–20:30. Each time period, a 5 min technical detection was carried out. At the same time, the No. 1 cross street in the South District was selected for video measurement and shooting, and the accuracy of the two-way cross-sectional human flow verification technology was recorded. After statistical processing of the human flow and human flow trajectories by street, model analysis is performed.

In order to ensure the accuracy and comprehensiveness of the data, we have decided to conduct additional data collection on the streets from 7 to 8 July 2024 to compensate for the shortcomings of the previously collected data [45]. After additional data collection, it was found that the data were highly consistent with those collected on 20–21 August 2023. This additional data collection initiative will help compensate for the lack of time span and provide a more comprehensive and accurate analysis foundation for the research. Through

such measures, we can be more confident that our research results are comprehensive and accurate, making our conclusions more credible.

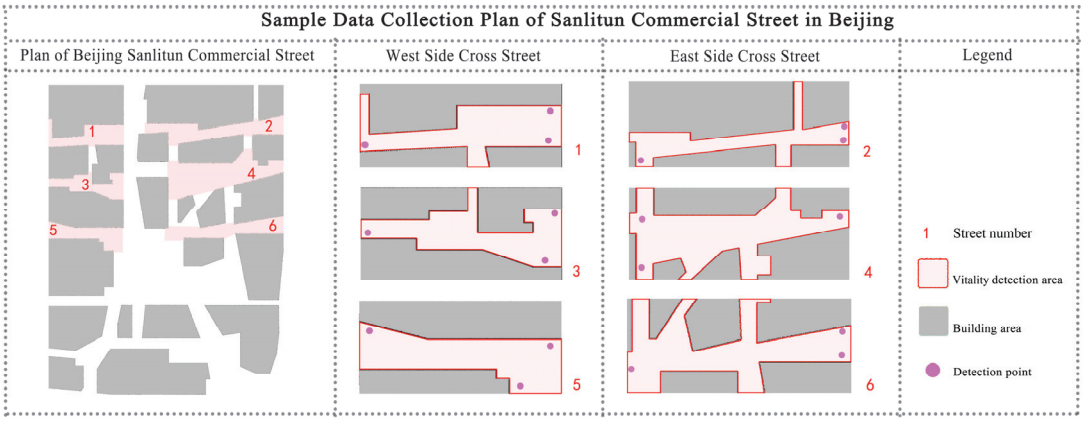



**Figure 2.** Sample data collection plan of sanlitun commercial street in Beijing.

### *3.3. Model Specification*

#### 3.3.1. Pedestrian Street Spatial Elements

(I) Store density (*SD*)

Store density [22] is defined as the number of stores per unit length of a commercial pedestrian street. In this study, store density is represented by the number of stores along the median of the street divided by the length of that median. Store density plays a crucial role in the spatial vitality of commercial pedestrian streets. A higher store density indicates a greater variety of shopping and service options available, which can attract more customers and tourists. This, in turn, increases pedestrian traffic and activity levels on the street, as presented in Table 1.

**Table 1.** Calculation methods for spatial element indicators of pedestrian streets.

| Spatial Element Indicators | Calculation Method |
| --- | --- |
| Store density ($P_s$) | The store density value is the ratio of the number of shops ($N_s$) on both sides of the street to the length of the median ($L_m$) line of the street. $P_s = \frac{N_s}{L_m}$ |
| Store type ($S_t$) | Calculate the type of store by calculating the sales type of the store ($S_t$). |
| Street width ($S_w$) | The calculation method for street width is the ratio of the total street area ($S_a$) to the median length of the street ($L_m$), which is the average street width. $S_w = \frac{S_a}{L_m}$ |
| Bottom permeability ($B_p$) | The calculation method for the permeability of the bottom ($B_p$) interface of the street is the ratio of the glass area along the street ($G_a$) to the facade area ($B_i$). $B_p = \frac{G_a}{B_i}$ |
| Number of chairs ($N_c$) | The number of public tables and chairs is recorded through observation and statistics. |
| Billboard area ($B_a$) | The advertising area is calculated by recording the length and width of advertising signs along the street, including street facade advertisements ($AF$), independent hanging advertisements ($AI$), and advertising signs ($AS$). $B_a = AF_l \times AF_d + AI_l \times AI_d + AS_l \times AS_d$ |

(II) Store type (*ST*)

Store type [23] refers to the variety of functional store categories found on commercial pedestrian streets. This metric reflects the diversity of shopping, dining, entertainment, and service options available. In this study, store types are categorized based on the types of products or services offered. A higher number of store types indicates a richer experience for pedestrians, providing a broader range of activities and interactions.

(III) Bottom interface permeability (*BP*)

Good ground floor interface permeability [24] enhances customer flow between the underground and ground levels. This facilitates increased pedestrian traffic, which in turn enhances store visibility and customer footfall, contributing to a vibrant and thriving business environment on the pedestrian street. A preliminary investigation indicates that the transmittance of the glass curtain wall on Sanlitun Commercial Street exceeds 80%. In this study, the ratio of the glass area to the facade area along the street is employed as the metric for calculating ground floor interface permeability.

(IV) Street width (*SW*)

The building height along Sanlitun Commercial Street is uniformly set to three floors [25]. Variations in pedestrian width influence the cross-sectional shape of the street. The SW of a commercial pedestrian street is intricately linked to its capacity for pedestrian traffic. Wider streets can accommodate more pedestrians, facilitating free movement and reducing congestion and pedestrian conflicts. In this study, street width is calculated as the average width, determined by dividing the total street area by the length of the line connecting the midpoints of the street's entrances and exits.

(V) Number of public tables and chairs (*NC*)

A sufficient number of public tables and chairs [26] can enhance social interaction and activity on commercial pedestrian streets. Comfortable seating facilities offer pedestrians places to rest and dine, potentially increasing their duration of stay. The quantity of tables and chairs is determined through systematic observation and recording.

(VI) Billboard area (*BA*)

Billboard area [27] enhances the spatial perception and visual appeal of commercial pedestrian streets. It provides navigation and information transmission functions that assist pedestrians in quickly locating their destinations or accessing necessary information. Clear and easily readable signage offers guidance that can facilitate pedestrian flow and encourage participation in commercial pedestrian areas. In this study, the advertising area was calculated by measuring the length and width of advertising signs along the street, including facade advertising, independent hanging signs, and other advertisements.

#### 3.3.2. Street Vitality Measurement

This study adopts the spatial vitality quantification model based on quantitative indicators proposed by Tong Niu as the method for measuring street vitality [36]. This model provides a practical and scientifically robust approach to assessing street vitality. It objectively quantifies vitality by incorporating various quantitative indicators, thus offering a comprehensive evaluation. The model's four quantitative indicators—number of people, residence time, trajectory diversity, and trajectory complexity—address key aspects such as human flow, activity duration, space utilization, and degree of interaction. These indicators facilitate a more detailed assessment of street vitality. Moreover, while the spatial vitality of commercial pedestrian streets predominantly reflects the attractiveness and busyness of different spaces, it does not necessarily capture directional business activities. Consequently, the quantification model proposed by Tong Niu is both scientific and comprehensive, making it well-suited for evaluating the spatial vitality of commercial pedestrian streets. By utilizing this method, the research can achieve objective and thorough evaluation results.

The calculation formula of the spatial vitality quantification model based on quantitative indicators is as follows (1):

$$Spatial\ Vitality = 0.582num + 0.254dur + 0.307TD + 0.159TC \quad (1)$$

In the street space, the vitality is determined by several factors. The number of pedestrians present in the area is represented by "*num*", while the duration of their stay is denoted as "*dur*". Additionally, the diversity of pedestrian trajectories is captured by "*TD*", and the complexity of pedestrian trajectories is measured by "*TC*".

(I) Number of people (*num*)

The attractiveness of a commercial pedestrian space can be assessed by the number of people present. A higher number of individuals in the same space often signifies greater appeal. In this study, the population count is determined by analyzing the number of pedestrian trajectories. To ensure accuracy, it is essential to deduplicate trajectories using the unique identifier of the device, such as the MAC address, to prevent tracking errors. Due to potential detection range errors, this study utilizes filtered trajectories. Consequently, the count of people excludes pedestrians who only briefly enter the spatial boundary or who travel along the boundary. These findings are summarized in Table 2.

(II) Residence time (*dur*)

This study calculates the dwell time by recording the number of track points marked by the trajectory timing. During data collection, track points are recorded at five-second intervals. Dwell time, defined as the average duration that pedestrians spend in a commercial street area, serves as an indicator of the space's attractiveness. This metric offers insights into the appeal of the space to pedestrians and their willingness to linger. The calculation is performed by analyzing the duration of the connection between WiFi detection equipment and pedestrians' devices. A higher number of stay track points typically indicates greater pedestrian attraction and interest in the commercial streets.

(III) Trajectory diversity (*TD*)

Higher vitality correlates with a richer array of activities, which is manifested in the diversity of pedestrian trajectories. This trajectory diversity illustrates variations in the structural patterns of pedestrian movement and captures the differences in paths taken by individuals within the space. Specifically, by collecting vector information that includes the starting and ending points of individual trajectories, one can calculate the structural similarity of these paths. These local vectors represent the shape and structure of pedestrian trajectories. Similarities or differences in these structures can indicate behavioral patterns of pedestrian groups or clusters.

(IV) Trajectory complexity (*TC*)

To account for behaviors that share the same trajectory but involve different activities, this study introduces the concept of trajectory complexity to calculate vitality values. For instance, when pedestrians traverse a space with identical starting and ending points, their movements tend to be purposeful, often lacking spontaneity. Such trajectories typically appear as simple straight lines, indicating a direct and efficient route to their destination. In contrast, trajectories associated with self-selected and social activities exhibit high randomness and significant variability, often appearing as wavy lines with frequent fluctuations. Variations in behaviors are primarily evidenced by the presence of inflection points in the trajectories and changes in the direction vectors at these points. Trajectories of passing pedestrians generally have few inflection points, and the variation in direction vectors between these points tends to be relatively uniform. On the other hand, trajectories of pedestrians engaged in leisure activities contain numerous inflection points, with notable variations in direction vectors observed between these points. The complexity of a trajectory is assessed by first identifying the inflection points and then calculating the vector differences by connecting adjacent inflection points.

**Table 2.** Tong Niu's trajectory-based vitality calculation method.

| Vitality Indicators | Calculation Method |
| --- | --- |
| Vitality ($V$) | The quantitative-indicator-based spatial vitality quantification model proposed by Tong Niu is a street vitality measurement method. The model consists of four quantifications, where $num$ is the number of people in the street space, $dur$ is the residence time of pedestrians, $TD$ is the diversity of pedestrian trajectories, and $TC$ is the complexity of pedestrian trajectories. The calculation method is as follows: $Spatial$ Vigour $= 0.582num + 0.254dur + 0.307TD + 0.159TC$ |
| Number of people ($num$) | The result of the number of people is obtained by recording the number of different trajectories, excluding pedestrians who enter the spatial boundary in a short period of time or travel along the boundary. |
| Duration of the timing ($dur$) | This article calculates the dwell time by recording the number of trajectory points marked during the trajectory timing. During the measurement process, the trajectory points ($T_p$) are recorded every 5 s, which means the dwell time is equal to the number of trajectory points in a single trajectory multiplied by 5. $dur = T_p \times 5$ |
| Trajectory diversity ($TD$) | Trajectory diversity reflects the structural differences in trajectories; that is, by collecting vector information composed of starting and ending points in a single trajectory, the similarity of its path structure is calculated. Among them, the difference in morphological structure between P (initial point) and Q (stopping point) is TD (P, Q), where trajectory $\{\rightarrow P\}_{i=1}$ and $P_{global}$ vectors, and trajectory Q is represented by $\{\rightarrow Q\}_{i=1}$ and $Q_{global}$ vectors. $TD(\mathrm{P},\mathrm{Q}) = \theta_{global} I_{global} \sum_{i=1}^{n} \theta_i I_i$ |
| Trajectory complexity ($TC$) | To calculate the trajectory complexity, the inflection points of each trajectory are extracted, and then their vector differences are extracted by connecting adjacent inflection points. $C_j$ is the complexity of the $j$-th trajectory, and $m$ is the number of trajectory segment vectors for the $j$-th trajectory. $\theta_{ij}$ and $I_{ij}$ are the angle and length differences in the $i+1$ trajectory segment vectors of the $i$-th and $j$-th trajectory segment vectors, respectively. $TC_j = \sum_{i=1}^{m-1} \theta_{ij} I_{ij}$ |

## 4. Results

### *4.1. The Spatial Feature Dataset of Streets*

The processed data on spatial elements include six major categories: *SD*, *ST*, *BP*, *SW*, *NC*, and *BA*. The classification and proportion of these elements are detailed in Table 3.

**Table 3.** Sanlitun commercial street elements survey form.

| Street Name | Store Density (%) | Store Type | Street Width (m) | Bottom Surface Permeability (%) | Number of Tables and Chairs | Advertising Area |
| --- | --- | --- | --- | --- | --- | --- |
| *Street 1* | 22 | 2 | 9.26 | 49.5 | 18 | 51 |
| *Street 2* | 16.9 | 4 | 5.88 | 53.4 | 33 | 25 |
| *Street 3* | 18 | 3 | 10.23 | 53.7 | 14 | 34 |
| *Street 4* | 12.4 | 6 | 12.03 | 51.5 | 52 | 15 |
| *Street 5* | 16.5 | 1 | 7.86 | 48.2 | 10 | 29 |
| *Street 6* | 15.1 | 3 | 7.69 | 53.8 | 24 | 40 |

In the east–west streets of Sanlitun, significant differences are observed in the data across various types of spatial elements. For instance, as depicted in Figure 3, Street 4 exhibits the highest value of six for store density, while Street 5 has the lowest at one, indicating that Street 4's value is six times that of Street 5. In terms of street width, Street 4 records the highest measurement at 12.03 m, compared to Street 2 at 5.88 m, marking an increase of 104.5%. Regarding ground floor interface permeability, Street 6 shows the highest value at 0.538, while Street 1 is the lowest at 0.495, an 8.6% increase. For the number of public tables and chairs, Street 4 leads with 52, significantly higher than Street 5, which has 10, an increase of 420%. In the billboard area, Street 1 features the largest area at 51 square meters, whereas Street 4 has the smallest at 15 square meters, showing an increase of 240%.

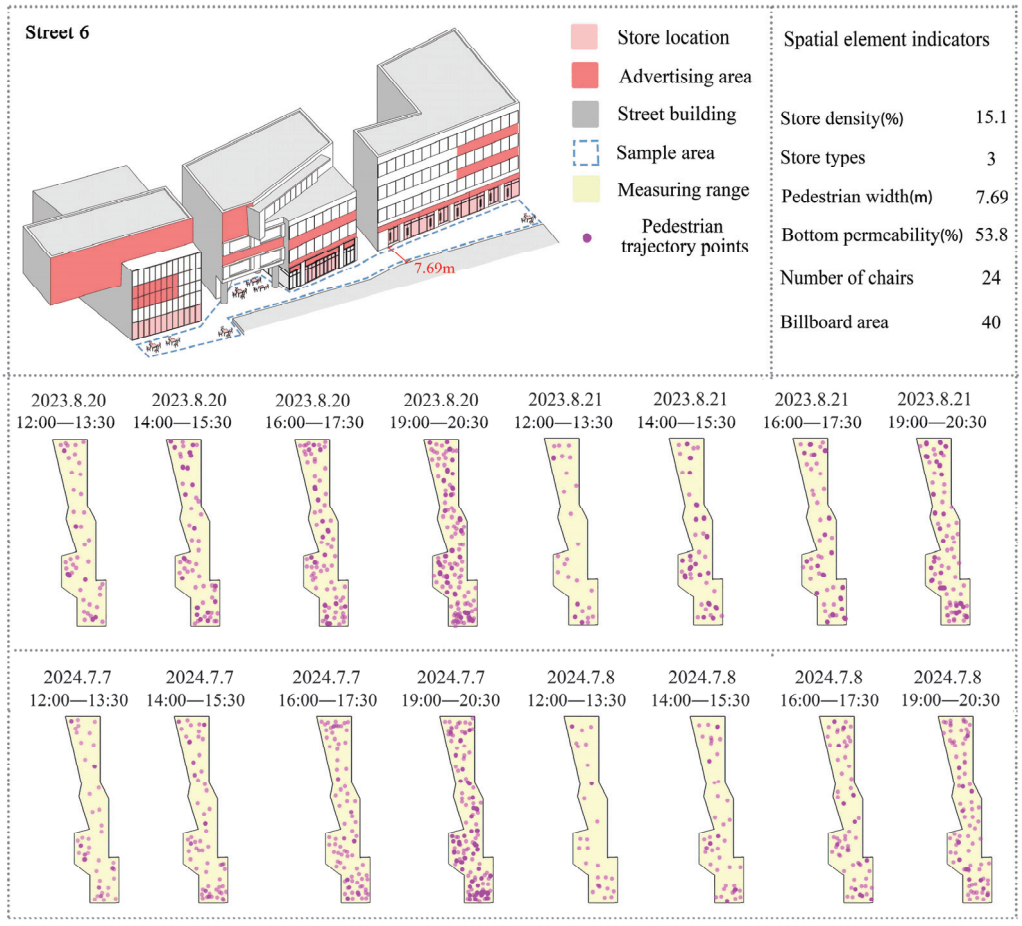



**Figure 3.** Schematic diagram of spatial parameters and vitality records for streets.

According to the data presented in the figure, among the six indicators—store density, store types, street width, number of public tables and chairs, and billboard area—Street 4 is representative in terms of store density, store types, street width, number of public tables and chairs, and billboard area. Street 1 is notably representative of store density, ground floor interface permeability, and billboard area. The spatial element data for Streets 4 and 1 exhibit significant differences. Additionally, Street 5 stands out in terms of shop types and the number of public tables and chairs, Street 2 is distinguished solely by its street width, and Street 6 is unique for its ground floor interface permeability. It is important to note that this study highlights the considerable variance in the spatial element data between Streets 4 and 1, providing a clearer understanding of the spatial diversity among different commercial streets. However, the presence of significant differences in spatial elements does not necessarily correlate with substantial differences in spatial vitality. Assessing spatial vitality requires detailed analysis through specific calculations.

### *4.2. Spatial Vitality Dataset of Streets*

This study analyzes pedestrian trajectory data from commercial streets collected via WiFi detection. The underlying principle involves the WiFi detection system actively scanning and capturing the signal characteristics of user devices, such as MAC addresses and signal strengths, when their WiFi functions are enabled. These characteristics, along with the distribution pattern of the signal, are used to precisely locate users within the street area. The data are confined to the street area and exclude the interiors of stores on either side of the street. Furthermore, to ensure data accuracy, detailed video observations and analyses were conducted. These confirmed that the data obtained from WiFi detection technology closely correspond to the actual pedestrian movements. This alignment is further discussed and validated in the subsequent verification phase.

The data collected include the number of people and individual trajectory information, yielding 5626 and 4452 records over two days, respectively. The recorded information is illustrated in the accompanying figure. The data collection methodology was developed with reference to relevant studies [46] and adhered to ethical research practices through several measures: firstly, permission for sample collection was obtained through negotiations with local law enforcement authorities; secondly, an agreement was signed with the management agency of the community where the data were gathered, stipulating that all personal information in the collected data would be anonymized and that the data would be used solely for research purposes, with no disclosure to third parties; thirdly, data recording occurred in outdoor public spaces, where pedestrians were informed about the data collection, emphasizing that the records are used exclusively for studying crowd behavior, not for individual tracking, and that personal information would be obscured.

### *4.3. Data Verification*

To ensure the accuracy of spatial vitality data, this study employs synchronous video recording for five minutes at each collection point during different time periods to capture bidirectional cross-sectional people flow activities at the measurement points. The data verification method consists of the following steps: (a) capturing video screenshots, (b) extracting pedestrian trajectories, and (c) transforming position coordinates [36]. Figure 4 details the specific processing procedure for each video: Initially, the research team selects clips from the video at the measurement point, ensuring each frame is smooth and stable. Subsequently, frame-by-frame analysis is conducted to pinpoint the pedestrian's trajectory. Given that the shape of pedestrian trajectories detected via WiFi differs from the video recording angle, the trajectory punctuation points recorded in the video are converted into vertical top-view trajectory points using the reference objects. This study employs the perspective transformation method (X, Y) to perform the coordinate transformation [47]. The primary aim of processing the data is to ascertain the consistency of the number of pedestrians, pedestrian residence time, trajectory coordinate points, and detection data in the video. While this verification method may not yield a flawless trajectory, and coordinate conversion might introduce errors, as well as tracking issues for severely occluded or excessively blurred individuals in the video may also generate inaccuracies, these factors minimally impact the quantitative analysis of vitality from the perspective of verifying spatial vitality elements. Future studies will incorporate more refined verification methods to enhance the accuracy of assessing the vitality of spatial elements in streets.

### *4.4. Regression Analysis of Spatial Vitality and Elements*

In this study, a correlation analysis of spatial vitality and elements is conducted using a method based on stepwise multiple linear regression. The fundamental principle of stepwise multiple linear regression is to automatically identify the most significant variables from a large pool of variables. This process helps establish a predictive or explanatory model for regression analysis [48]. Specifically, the model will first include the variables with the highest correlation with the dependent variable. Subsequently, the method adds the next most relevant variable to the model until no other variables demonstrate statistical

significance. During this iterative process, it is possible to exclude a variable that was previously included in a step but is no longer statistically significant. This study used the SPSS platform for regression analysis calculations [49]. Through regression analysis, this study obtained the optimal energy quantification model at different times. Among them, the independent variables are store density, store type, ground floor interface permeability, street width, number of public tables and chairs, and billboard area, and the dependent variable is the spatial vitality value.

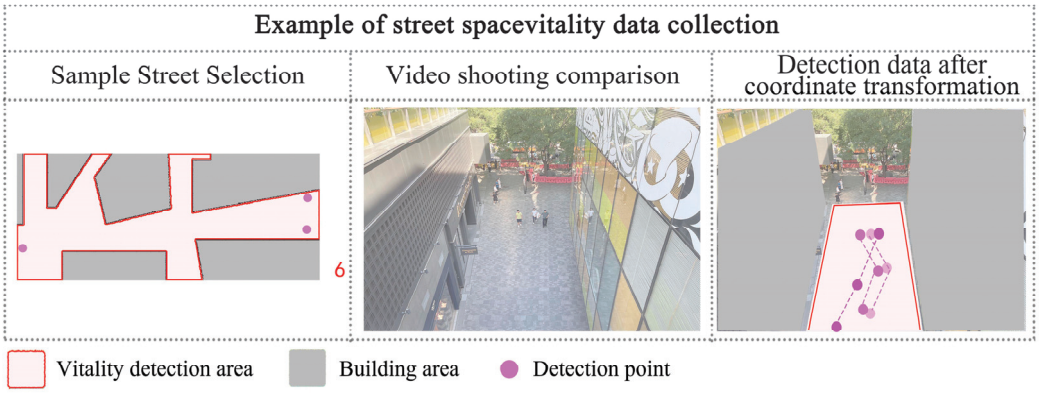



**Figure 4.** Schematic diagram of spatial parameters and vitality records for Street 6.

The research results show that in the multiple linear regression model established between 19:00 and 20:30 on non-working days, the significance of store type and advertising area are 0.143 and 0.529, respectively. There is no significant difference in store type and advertising area at the 0.05 level. In the multiple linear regression model developed for the remaining time periods, all variables included in the model exhibit statistical significance at the 0.05 significance level.

Based on the analysis, it can be inferred that during non-working days from 19:00 to 20:30, the vitality of the street space is influenced by factors such as the density of shops, the permeability of the ground floor interface, the width of walkways, and the presence of public tables and chairs. The rest of the time, the vitality of street space is affected by store density, store types, ground floor interface permeability, pedestrian width, number of public tables and chairs, and billboard area.

#### 4.4.1. Analysis Results of Different Spatial Characteristics

In this study, there are two sets of correlations between spatial elements and spatial vitality. In the special vitality model, focusing on the time period from 19:00 to 20:30 on non-working days, street spatial vitality is correlated with store density, ground floor interface permeability, and pedestrian width.

(I) Normal vitality model

This study utilizes the results obtained from stepwise multiple linear regression analysis models. It reveals that across all normal models investigated, certain findings can be derived. Store density and advertising area are negatively correlated with spatial vitality, while store type, ground floor interface permeability, street width, and the number of public tables and chairs are positively correlated with spatial vitality. The third model in the regression parameter graph shows a significant spatial weight difference in the analysis model between 16:00 and 17:30 on non working days.

The results show that tolerance values of store density (*SD*), store type (*ST*), ground floor interface permeability (*BP*), street width (*PW*), number of public tables and chairs (*NC*), and billboard area (*BA*) are 1.1, 0.7, 1.1, 0.3, 0.5, and 0.5, respectively. All the coefficients, which are all greater than 0.1, indicate that there is no significant covariance between the independent variables and other variables in this study. SPSS 26 statistical analysis software was used to conduct a linear regression analysis on store density, store type, ground floor

interface permeability, street width, number of public tables and chairs, billboard area and spatial vitality, and a regression model of street space design parameters on spatial vitality was obtained, as shown in Equation (2).

$$Y = -0.839SD + 1.377ST + 0.657BP + 1.717SW + 0.546NC - 0.039BA - 22.163 \quad (2)$$

Among them, $Y$ is the street space vitality, $SD$ is the store density, $ST$ is the store type, $BP$ is the permeability of the ground floor interface, $PW$ is the street width, $NC$ is the number of public tables and chairs, and $BA$ is the billboard area.

The findings from the linear regression analysis are displayed in Figure 1. These coefficients enable the comparison of the influence of street space design parameters on overall vitality, even though they may have varying magnitudes and units. The standardized factor β is a quantitative index utilized to standardize different quantitative units, indicating the effectiveness of the independent variable on the dependent variable. The street width has a standardized coefficient of 1.717, whereas the billboard area has a standardized coefficient of $-0.039$. The influence of pedestrian width on street vitality is 44.02 times greater than that of the billboard area, and the multiple correlation coefficient is 0.645. The coefficient of determination is a statistical measure indicating the effectiveness of model fitting; the model's fitting effect improves as it approaches one. Hence, the equation demonstrates a high level of fit, indicating a strong linear relationship between street space design parameters and spatial vitality.

(II) Special vitality model

This study utilizes the results obtained from the stepwise multiple linear regression analysis model. The findings demonstrate that in the model of spatial vitality, certain relationships and patterns can be observed. Store density is negatively correlated with spatial vitality, while ground floor interface permeability, street width, and the number of public tables and chairs are positively correlated with spatial vitality. For non-working days, the 19:00–20:30 model is analyzed, which is the fourth model in the model regression parameter diagram.

The results show that the tolerance values of store density (*SD*), ground floor interface permeability (*BP*), pedestrian width (*PW*), and number of public tables and chairs (*NC*) are 1.1, 1.1, 0.3, and 0.5, respectively, all greater than 0.1, the analysis indicates that there is no covariance between the independent variable and other variables, as all coefficients demonstrate no significant association. SPSS 26 statistical analysis software was used to conduct linear regression analysis on store density, ground floor interface permeability, street width, number of public tables and chairs, and spatial vitality, and the obtained regression model illustrates the relationship between street space design parameters and spatial vitality, as shown in Equation (3).

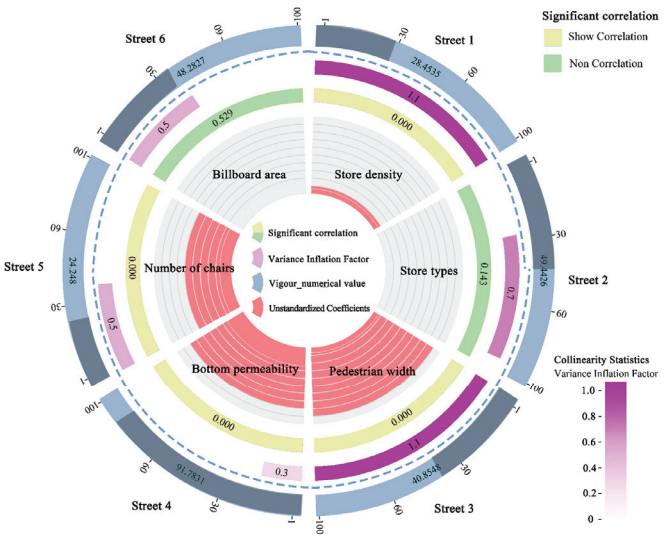
$$Y = -1.722SD + 1.253BP + 2.745SW + 0.9376NC - 39.27 \quad (3)$$

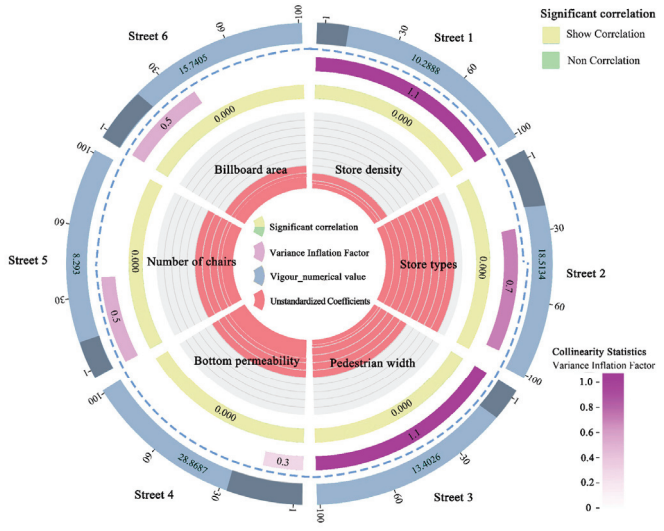
Among them, $Y$ is the vitality of street space, $SD$ is the density of shops, $BP$ is the permeability of the ground floor interface, $PW$ is the street width, and $NC$ is the number of public tables and chairs.

Figure 5 presents the results obtained from the linear regression analysis. These coefficients facilitate the comparison of the effects of street space design parameters on overall vitality despite their varying magnitudes and measurement units. The standardized factor β is a quantitative index employed to standardize diverse measurement units, signifying the effectiveness of the independent variable on the dependent variable. The street width has a standardized coefficient of 2.745, while the number of public tables and chairs has a standardized coefficient of 0.9376. The impact of street width on street vitality is 2.92 times that of the number of public tables and chairs, and the multiple correlation coefficient is 0.735. The coefficient of determination is a statistical measure indicating the effectiveness of model fitting; the model's fitting effect improves as it approaches one.

Thus, the equation demonstrates a high level of fit, suggesting a strong linear relationship between street space design parameters and spatial vitality.

**Figure 5.** *Cont.*



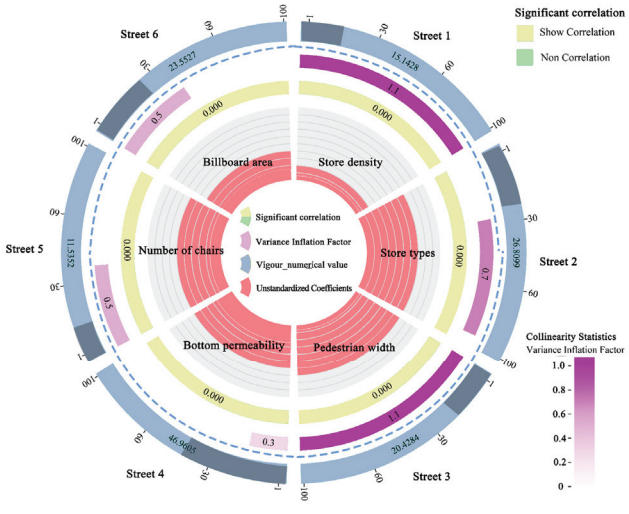




**Figure 5.** *Cont.*

**Figure 5.** Model regression parameter diagrams.

4.4.2. Analysis Results of Different Time Characteristics

In this study, it was found that the standardized factor difference varied significantly between working days and non-working days, indicating that the efficiency of street parameters on street vitality changes over time. The results show that on non-working days, the standardized coefficient of street width at noon is 0.521, accounting for 16.52%, and the standardized coefficient at night is 2.745, accounting for 41.23%. The street width is more efficient at improving street vitality at night than at noon by 2.49 times, while the standardized coefficient of the number of tables and chairs at noon is 0.352, accounting for 11.16%, and the standardized coefficient at night is 0.937, accounting for 14.07%. The efficiency of the number of tables and chairs in improving street vitality at night is 1.269 times that at noon. The findings indicate that over time, the influence of street width and the number of tables and chairs on enhancing street vitality increases gradually. Notably, the impact of street width on effectiveness exhibits the highest rate of growth in improving street vitality, as shown in Figure 6.

On weekdays, the standardized coefficient of street width at noon is 0.338, accounting for 14.42%, and the standardized coefficient at night is 1.835, accounting for 28.91%. The efficiency of street width in improving street vitality at night is 2.01 times that at noon;

The standardized coefficient of store types at noon is 1.192, accounting for 50.91%, and the standardized coefficient at night is 2.419, accounting for 38.12%. The efficiency of store types in improving street vitality at night is 0.748 times that at noon. It shows that with the increase in time, the impact of street width on the improvement in street vitality is gradually increasing, and the impact of store types on the improvement in street vitality is gradually declining, among which the efficiency of street width has the fastest growth.

It shows that as time goes from noon to night, the efficiency of street width in street space design parameters in improving street vitality is more significant, by 2.49 times on non-working days and by 2.01 times on working days. The efficiency of store types in improving street vitality is low. The working day is not affected; the working day is 0.748 times. As time changes, the vitality-improving efficiency of street space design parameters from large to small is pedestrian width, ground floor interface permeability, number of tables and chairs, store density, billboard area, and store types.

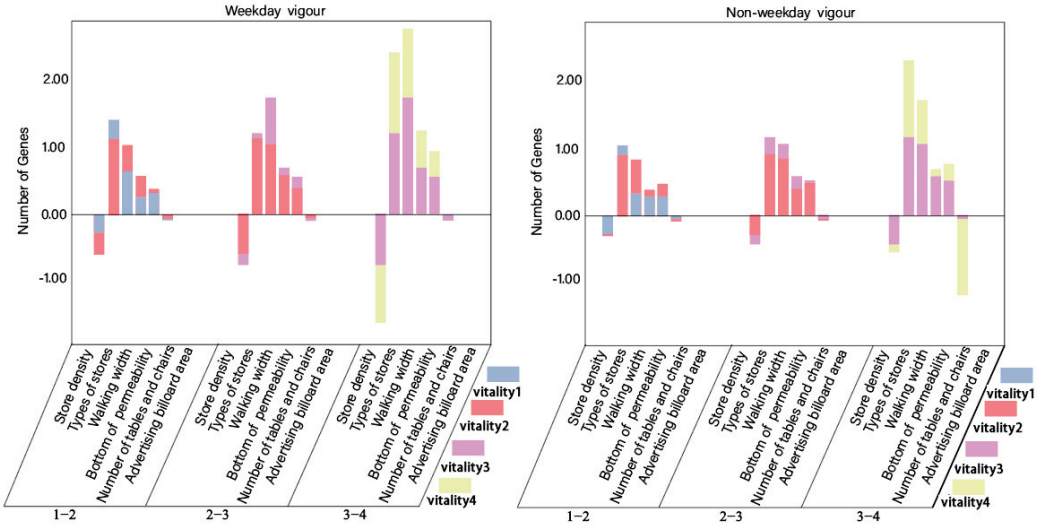



**Figure 6.** The effectiveness impact of various street elements on enhancing street vitality at different time periods.

## 5. Discussion

### *5.1. Selection of Spatial Elements under Spatial Characteristics*

Disregarding temporal characteristics and focusing solely on spatial attributes, significant variations are observed in the impact of different street elements on vitality. Specifically, within the street width range of 5.88 m to 10.83 m, there is a positive correlation between street width and street vitality, suggesting that an increase in street width generally enhances vitality. This discovery does not conflict with the idea that narrower streets are more accessible. Jan Gehl pointed out in "Cities For People" that the scale of streets close to people is below 15 m, and the two are not contradictory. The premise of this discovery is based on research results within the same commercial district. However, it is important to note that excessively narrow streets can lead to congestion and traffic issues, thereby adversely affecting street vitality. Therefore, this correlation underscores a nuanced relationship between street width and vitality; within the specified range, an expansion in street width is likely to boost vitality to some extent [50].

Moreover, within the shop density range of 12% to 22%, there is a negative correlation between shop density and street vitality. Increased shop density tends to diminish street vitality, potentially due to heightened competition among businesses and diminished appeal of individual shops, which collectively detract from the overall street vitality [51].

### *5.2. Daytime Street Element Selection under Time Characteristics*

Focusing solely on time characteristics during daylight hours, there is a noticeable difference in how street elements impact vitality. Specifically, from 12:00 to 17:30, there is a positive correlation between time and street vitality. As the day progresses, the total number of people on the street gradually increases, enhancing vitality more rapidly in conjunction with wider street widths and higher penetration rates of the ground floor interface. Between 16:00 and 17:30, the six streets surveyed reached their peak daytime vitality, with the highest recorded value being 74.7406. Streets that feature higher ground floor interface permeability, diverse store types, and an abundance of tables and chairs tend to attract more people. In the spatial design of commercial pedestrian streets operational during daylight hours, the focus should be on maximizing street width, which shows the fastest growth in vitality, followed by the permeability of the ground floor interface, store variety, and the availability of tables and chairs.

### *5.3. Nighttime Street Element Selection under Time Characteristics*

Considering only the temporal characteristics of nighttime, the impact of various street elements on vitality shows notable differences, with advertising area and store type demonstrating no significant correlation to street vitality. During the hours of 19:00 to 20:30 on non-working nights, street width, store density, ground floor interface permeability, and the presence of tables and chairs emerge as the critical factors influencing vitality. The peak nighttime vitality is observed at a street vitality index of 91.7831, coinciding with the maximum pedestrian count. The contribution of street width to enhancing nighttime vitality is 2.49 times greater than at noon on non-working days, 2.01 times more than on working days, and 2.92 times higher than the impact of tables and chairs. Thus, in designing commercial pedestrian streets with a focus on the nighttime economy, it is advisable to prioritize street width due to its significant influence on vitality. This should be followed by optimizing ground floor interface permeability and the strategic placement of tables and chairs while minimizing the diversity of store types.

## 6. Conclusions

In this research, a comprehensive dataset of pedestrian trajectories on commercial pedestrian streets was compiled, introducing a people-centric vitality evaluation system aimed at assessing overall street vitality and constructing a dataset with a specific focus on this aspect. This study explores the correlation between spatial vitality and several variables, *SD*, *ST*, *BP*, *SW*, *NC*, and *BA*, to derive a model that accurately quantifies vitality. Experimental findings confirm that the methodology proposed herein accurately evaluates the influence of street design parameters on overall vitality. The vitality quantification model presented shows a higher accuracy in fitting overall vitality than models relying solely on superficial attributes such as pedestrian count and dwell time. This research surpasses traditional observational and behavioral recording techniques, offering a precise assessment of street design elements. The results provide a crucial reference for further quantitative research on the interaction between the environment and human behavior. It should be noted that due to data collection constraints, this study focuses on a 5 min visual technology detection of each street space, limiting the analysis to spatial vitality within this brief timeframe. Future research will extend the analysis to longer periods and explore temporal variations in vitality accuracy.

This research article presents findings aimed at identifying design parameters that influence the vitality of street spaces, offering an innovative methodology for the meticulous design of commercial pedestrian streets. The employed vitality quantification method serves to assess and refine design schemes, aligning with the goal of augmenting architectural design specifications. The developed workflow facilitates real-time evaluation and comparative analysis of spatial vitality in design schemes for commercial pedestrian streets. Importantly, this workflow retains its applicability even when fluctuations occur in the pedestrian traffic on the commercial street.

**Author Contributions:** Conceptualization, J.Z., W.Z. and H.L.; methodology, W.Z.; software, W.Z.; validation, J.Z., W.Z. and H.L.; formal analysis, W.Z.; investigation, W.Z.; resources, J.Z.; data curation, W.Z.; writing—original draft preparation, J.Z., W.Z., H.L. and R.H.; writing—review and editing, J.Z., W.Z., H.L. and R.H.; visualization, R.H.; supervision, J.Z.; project administration, J.Z.; funding acquisition, W.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Hebei Province social Science Foundation, grant number HB19YS039.

**Data Availability Statement:** No new data were created or analysed in this study. Data sharing is not applicable to this article.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Gandy, M. Berlin bodies: Anatomizing the streets of the city, by Stephen Barber: London, Reaktion, 2017. *J. Urban Aff.* **2020**, *42*, 285–286. [CrossRef]
2. Leichtle, T.; Taubenböck, H. Urbanization that Hides in the Dark-Spotting China's "Ghost Neighborhoods" from Space. *Landsc. Urban Plan.* **2020**, *200*, 103822.
3. Döringer, S.; Uchiyama, Y.; Penker, M.; Kohsaka, R. A meta-analysis of shrinking cities in Europe and Japan. Towards an integrative research agenda. *Eur. Plan. Stud.* **2020**, *28*, 1693–1712. [CrossRef]
4. Nia, H.A.N. The role of urban aesthetics on enhancing vitality of urban spaces. *Khulna Univ. Stud.* **2021**, *18*, 59–77.
5. Le Borgne, S. Coping with urban shrinkage: The role of informal social capital in French medium-sized shrinking cities. *Eur. Plan. Stud.* **2024**, *32*, 569–585. [CrossRef]
6. Li, Q.; Cui, C.; Liu, F.; Wu, Q.; Run, Y.; Han, Z. Multidimensional urban vitality on streets: Spatial patterns and influence factor identification using multisource urban data. *ISPRS Int. J. Geo-Inf.* **2021**, *11*, 2. [CrossRef]
7. Bertolini, L. From "streets for traffic" to "streets for people": Can street experiments transform urban mobility? *Transp. Rev.* **2020**, *40*, 734–753. [CrossRef]
8. Liang, Y.; D'uva, D.; Scandiffio, A.; Rolando, A. The more walkable, the more livable?—Can urban attractiveness improve urban vitality? *Transp. Res. Procedia* **2022**, *60*, 322–329. [CrossRef]
9. Jiang, Y.; Han, Y.; Liu, M.; Ye, Y. Street vitality and built environment features: A data-informed approach from fourteen Chinese cities. *Sustain. Cities Soc.* **2022**, *79*, 103724. [CrossRef]
10. Liu, B.; Qing, L.; Han, L.; Ying, L. Research on Public Space Vitality Representation Based on Space Trajectory Entropy. *Landsc. Archit.* **2022**, *29*, 95–101. [CrossRef]
11. Zhao, K.; Guo, J.; Ma, Z.; Wu, W. Exploring the Spatiotemporal Heterogeneity and Stationarity in the Relationship between Street Vitality and Built Environment. *SAGE Open* **2023**, *13*, 21582440231152226. [CrossRef]
12. Xiana, H. Simulation of pedestrian flow in traditional commercial streets based on space syntax. *Procedia Eng.* **2017**, *205*, 1344–1349. [CrossRef]
13. Yue, W.; Chen, Y.; Zhang, Q.; Liu, Y. Spatial explicit assessment of urban vitality using multi-source data: A case of Shanghai, China. *Sustainability* **2019**, *11*, 638. [CrossRef]
14. Ma, X.; Ma, C.; Wu, C.; Xi, Y.; Yang, R.; Peng, N.; Zhang, C.; Ren, F. Measuring human perceptions of streetscapes to better inform urban renewal: A perspective of scene semantic parsing. *Cities* **2021**, *110*, 103086. [CrossRef]
15. Li, Z.; Sun, X.; Zhao, S.; Zuo, H. Integrating eye-movement analysis and the semantic differential method to analyze the visual effect of a traditional commercial block in Hefei, China. *Front. Archit. Res.* **2021**, *10*, 317–331. [CrossRef]
16. Gan, X.; Huang, L.; Wang, H.; Mou, Y.; Wang, D.; Hu, A. Optimal block size for improving urban vitality: An exploratory analysis with multiple vitality indicators. *J. Urban Plan. Dev.* **2021**, *147*, 04021027. [CrossRef]
17. Wu, W.; Niu, X. Influence of built environment on urban vitality: Case study of Shanghai using mobile phone location data. *J. Urban Plan. Dev.* **2019**, *145*, 04019007. [CrossRef]
18. Sun, Z.; Bell, S.; Scott, I.; Qian, J. Everyday use of urban street spaces: The spatio-temporal relations between pedestrians and street vendors: A case study in Yuncheng, China. *Landsc. Res.* **2020**, *45*, 292–309. [CrossRef]
19. Chen, J.; Tian, W.; Xu, K.; Pellegrini, P. Testing Small-Scale Vitality Measurement Based on 5D Model Assessment with Multi-Source Data: A Resettlement Community Case in Suzhou. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 626. [CrossRef]
20. Yang, C.; Qian, Z. Street network or functional attractors? Capturing pedestrian movement patterns and urban form with the integration of space syntax and MCDA. *Urban Des. Int.* **2023**, *28*, 3–18. [CrossRef]
21. Li, S.; Ma, S.; Tong, D.; Jia, Z.; Li, P.; Long, Y. Associations between the quality of street space and the attributes of the built environment using large volumes of street view pictures. *Environ. Plan. B Urban Anal. City Sci.* **2022**, *49*, 1197–1211. [CrossRef]
22. Fang, K.; Wang, X.; Chen, L.; Zhang, Z.; Furuya, N. Research on the correlation between pedestrian density and street spatial characteristics of commercial blocks in downtown area: A case study on Shanghai Tianzifang. *J. Asian Archit. Build. Eng.* **2019**, *18*, 233–246. [CrossRef]

23. Hu, X.; Ren, Y.; Tan, Y.; Shi, Y. Research on the Spatial and Temporal Dynamics of Crowd Activities in Commercial Streets and Their Relationship with Formats—A Case Study of Lao Men Dong Commercial Street in Nanjing. *Sustainability* **2023**, *15*, 16838. [CrossRef]
24. Xu, G.; Zhong, L.; Wu, F.; Zhang, Y.; Zhang, Z. Impacts of Micro-Scale Built Environment Features on Tourists' Walking Behaviors in Historic Streets: Insights from Wudaoying Hutong, China. *Buildings* **2022**, *12*, 2248. [CrossRef]
25. Zhang, L.; Zhang, R.; Yin, B. The impact of the built-up environment of streets on pedestrian activities in the historical area. *Alex. Eng. J.* **2021**, *60*, 285–300. [CrossRef]
26. Li, Y.; Yabuki, N.; Fukuda, T. Exploring the association between street built environment and street vitality using deep learning methods. *Sustain. Cities Soc.* **2022**, *79*, 103656. [CrossRef]
27. Kangyan, D. Impact of Outdoor Store Signboards on Street Vitality: A Case Study of Ximazhuang Street in Nanchang City. *J. Landsc. Res.* **2020**, *12*, 105. [CrossRef]
28. Mu, B.; Liu, C.; Mu, T.; Xu, X.; Tian, G.; Zhang, Y.; Kim, G. Spatiotemporal fluctuations in urban park spatial vitality determined by on-site observation and behavior mapping: A case study of three parks in Zhengzhou City, China. *Urban For. Urban Green.* **2021**, *64*, 127246. [CrossRef]
29. Liu, S.; Lai, S.-Q.; Liu, C.; Jiang, L. What influenced the vitality of the waterfront open space? A case study of Huangpu River in Shanghai, China. *Cities* **2021**, *114*, 103197. [CrossRef]
30. Kim, Y.L. Seoul's Wi-Fi hotspots: Wi-Fi access points as an indicator of urban vitality. *Comput. Environ. Urban Syst.* **2018**, *72*, 13–24. [CrossRef]
31. Liu, S.; Lai, S. Measurement of Urban Public Space Vitality Based on Big Data. *Landsc. Archit.* **2019**, *26*, 24–28.
32. Zheng, J.; He, J.; Tang, H. The vitality of public space and the effects of environmental factors in Chinese suburban rural communities based on tourists and residents. *Int. J. Environ. Res. Public Health* **2022**, *20*, 263. [CrossRef]
33. Hou, J.; Chen, L.; Zhang, E.; Jia, H.; Long, Y. Quantifying the usage of small public spaces using deep convolutional neural network. *PLoS ONE* **2020**, *15*, e0239390. [CrossRef]
34. Williams, S.; Ahn, C.; Gunc, H.; Ozgirin, E.; Pearce, M.; Xiong, Z. Evaluating sensors for the measurement of public life: A future in image processing. *Environ. Plann. B: Urban Anal. City Sci.* **2019**, *46*, 1534–1548. [CrossRef]
35. Yan, W.; Forsyth, D.A. Learning the behavior of users in a public space through video tracking. In Proceedings of the 2005 Seventh IEEE Workshops on Applications of Computer Vision (WACV/MOTION'05), Breckenridge, CO, USA, 5–7 January 2005; pp. 370–377. [CrossRef]
36. Niu, T.; Qing, L.; Han, L.; Long, Y.; Hou, J.; Li, L.; Tang, W.; Teng, Q. Small public space vitality analysis and evaluation based on human trajectory modeling using video data. *Build. Environ.* **2022**, *225*, 109563. [CrossRef]
37. Sommer, R. *Social Design: Creating Buildings with People in Mind*; Prentice Hall Inc.: Upper Saddle River, NJ, USA, 1983.
38. Moore, R.C.; Cosco, N.G. Using behaviour mapping to investigate healthy outdoor environments for children and families: Conceptual framework, procedures and applications. *Innov. Approaches Res. Landsc. Health Open Space People Space* **2010**, *2*, 33–73.
39. Zordan, M.; Talamini, G.; Villani, C. The Association between Ground Floor Features and Public Open Space Face-To-Face Interactions: Evidence from Nantou Village, Shenzhen. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4934. [CrossRef]
40. Villani, C.; Talamini, G. Pedestrianised streets in the global neoliberal city: A battleground between hegemonic strategies of commodification and informal tactics of commoning. *Cities* **2021**, *108*, 102983. [CrossRef]
41. Villani, C.; Talamini, G. Making Vulnerability Invisible: The Impact of COVID-19 on the Use of Public Space in Hong Kong. *J. Plan. Educ. Res.* **2023**, *1*, 16. [CrossRef]
42. Kang, C.; Fan, D.; Jiao, H. Validating activity, time, and space diversity as essential components of urban vitality. *Environ. Plan. B Urban Anal. City Sci.* **2021**, *48*, 1180–1197. [CrossRef]
43. Xu, Y.; Chen, X. The spatial vitality and spatial environments of urban underground space (UUS) in metro area based on the spatiotemporal analysis. *Tunn. Undergr. Space Technol.* **2022**, *123*, 104401. [CrossRef]
44. Jiang, C.; Cheng, G. The Way of the Ease Traffic Congestion in Commercial Center of Beijing—The Analysis and Research of Level Analyses and Fuzzy Evaluation in Sanlitun Street. In Proceedings of the 22nd International Conference on Industrial Engineering and Engineering Management 2015: Core Theory and Applications of Industrial Engineering (Volume 1); Atlantis Press: Paris, France, 2016; pp. 51–61.
45. Cohen, J.; Cohen, P.; West, S.G.; Aiken, L.S. *Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences*; Routledge: New York, NY, USA, 2013.
46. Wu, W.; Ma, Z.; Guo, J.; Niu, X.; Zhao, K. Evaluating the effects of built environment on street vitality at the city level: An empirical research based on spatial panel Durbin model. *Int. J. Environ. Res. Public Health* **2022**, *19*, 1664. [CrossRef] [PubMed]
47. Eiter, T.; Mannila, H. Computing Discrete Fréchet Distance. Technical Report. 1994. Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.90.937&rep=rep1&type=pdf (accessed on 10 March 2024).
48. Azemati, S.; Saleh Sedghpour, B. Feasibility study of improving the level of vitality in university open space from the perspective of space users by structural equation modeling method. *J. Sustain. Archit. Urban Des.* **2021**, *9*, 215–227. [CrossRef]
49. Wang, H.; Yang, F.; Liu, L. Comparison and application of standardized regressive coefficient and partial correlation coefficient. *J. Q. Tech. Econ.* **2006**, *9*, 150–155. Available online: http://en.cnki.com.cn/Article_en/CJFDTOTAL-SLJY200609016.htm (accessed on 10 March 2024).

50. Gehl, J. *Cities for People*; Island Press: Washington, DC, USA, 2013.
51. Pons, F.; Giroux, M.; Mourali, M.; Zins, M. The relationship between density perceptions and satisfaction in the retail setting: Mediation and moderation effects. *J. Bus. Res.* **2016**, *69*, 1000–1007. [CrossRef]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# Rural Environmental Quality Evaluation Indicator System: Application in Shangluo City, Shaanxi Province

**Chenxi Li [1,2], Qiao Liu [1,*], Zhihong Zong [1] and Yingying Fang [1]**

[1] School of Public Administration, Xi'an University of Architecture and Technology, Xi'an 710055, China; lichenxi@xauat.edu.cn (C.L.); zongzhihong@xauat.edu.cn (Z.Z.); fangyingying@xauat.edu.cn (Y.F.)
[2] State Key Laboratory of Green Building in Western China, Xi'an University of Architecture and Technology, Xi'an 710055, China
* Correspondence: liuqiao@xauat.edu.cn

**Abstract:** The evaluation of rural environmental quality plays an important role in improving farmers' quality of life and in realizing a livable, workable, and beautiful countryside. Taking Shangluo City in Shaanxi Province as the study area, 16 indicators across five systems were selected to evaluate the rural environmental quality. The following methods were used in the evaluation: the hierarchical analysis method, the expert scoring method, and the fuzzy comprehensive evaluation method. The results show the following: (1) The rural environmental quality assessment value of Shangluo City is adequate. (2) In the system layer, the toilet renovation and infrastructure scores were high; however, the household sewage treatment and the construction and management mechanisms need to be improved. (3) According to an IPA quadrant diagram, the importance and satisfaction values for each index varied significantly. The management of black, foul-smelling water bodies and action on environmental remediation emerged as key to improving rural environmental quality. This study can provide a reference for the comprehensive improvement of rural environmental quality in other areas of Shaanxi Province.

**Keywords:** rural environment; analytic hierarchy process; fuzzy comprehensive evaluation method; Shangluo City

**Citation:** Li, C.; Liu, Q.; Zong, Z.; Fang, Y. Rural Environmental Quality Evaluation Indicator System: Application in Shangluo City, Shaanxi Province. *Sustainability* **2024**, *16*, 3198. https://doi.org/10.3390/su16083198

Academic Editor: Gema Cárdenas

Received: 20 February 2024
Revised: 6 April 2024
Accepted: 9 April 2024
Published: 11 April 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The human settlement environment is a complex system, which is centered on people. It comprises villages, towns, cities, and other settlements. Human settlements also require the infrastructure necessary for survival and the natural and social environments that humans rely on for their life and production [1]. The quality of the rural environment is an issue of concern in contemporary social sciences [2]. As a key indicator for evaluating farmers' quality of life, the rural environment is directly related to the production, life, and ecological health of rural areas. Equally, it is also one of the core components in promoting the integration of urban and rural areas in China, in promoting the construction of new towns and cities, and in implementing the strategy of comprehensive rural revitalization. To date, many villages, nationwide, have gradually transitioned from "ecological poverty alleviation" to "ecological revitalization" and from "village cleanliness" to "ecological livability". Thus, they have entered a new stage in constructing livable and beautiful villages. However, some villages are at different levels in terms of their economy, infrastructure, and ecological environment, which has meant that plans to upgrade the quality of the rural environment still suffer from problems such as insufficient capital investment, difficulty in maintaining the long-term effects, limited public awareness of environmental protection, and unsound management mechanisms. These are serious impediments to rural economic development and the well-being of farmers [3]. Consequently, building an indicator evaluation system that accurately assesses rural environmental quality and for-

mulates locally relevant countermeasures for improvement is a key problem in improving rural environmental quality, and one which must be solved.

The concept of the human settlement was first proposed by Doxiadis, who divided it into urban settlements and rural settlements [4]. Other scholars have taken the lead in conducting work on rural settlements, focusing on the following [5]: rural environmental pollution [6], sustainable rural development [7], and rural human settlement environment issues [8]. The following methods are commonly adopted in the evaluation of rural environmental quality and have been widely used in subsequent research: the questionnaire method [9], the hierarchical analysis method [10], the entropy weight method [11], and other evaluation methods. Although domestic scholars' research on the rural environment started relatively late, the continuous implementation of the rural revitalization strategy has further extended and expanded the research content in this area: it has progressed from large-scale considerations, such as early disease control, house construction, and water conservancy construction, to more specific considerations, such as rural waste, sewage treatment, toilet revolution, and village appearance. This increased scope has promoted the development of practical issues related to rural environment management [12,13]. Since the implementation of the Three-Year Action Program for Rural Human Settlement Environment Improvement in 2018, rural environment-related research has received extensive attention from scholars in China. This research has mainly focused on analyzing the current situation [14,15], spatial and temporal differentiation and influencing factors [16], and remediation models and optimization paths [17,18]. At present, rural environmental quality evaluations are mainly based on statistical data and questionnaire data. These data focus on indicators such as the construction of economic development, infrastructure, and the ecological environment [19–21]. The entropy weighting method, the full-aligned polygonal composite index method, the fuzzy comprehensive evaluation method, and other quantitative methods are used to evaluate the advantages and disadvantages of the rural environmental quality in provincial areas, urban agglomerations, county areas, economic zones, and other areas [22–24].

In summary, scholars have achieved significant results in the study of the rural environment, but the following issues need to be explored further: First, most of the existing studies are concentrated in the eastern and central regions of China, and the level of China's rural environment, in general, shows a trend of decreasing from east to west; however, few studies have evaluated the rural environmental quality in Shaanxi Province. Second, the existing data sources for rural environmental improvement studies focus on cross-sectional data, and the evaluation indicator system focuses on the economic development and infrastructure of the study area, which can hardly reflect the actual situation of the area. Third, although there are more research studies on the evaluation of the rural environment, few studies have focused on evaluating the rural environmental quality based on the micro perspective. Therefore, based on the field research data, in this study, we focused on the farmers in 12 villages, across three counties in Shangluo City, as the research object. This study combined the objectives and tasks mentioned in the Five-Year Action Program for Rural Human Settlement Environment Improvement in Shaanxi Province (2021–2025), constructed the index evaluation system, and carried out an evaluation of the rural environmental quality and an analysis of the countermeasures for enhancement. This will provide useful support in the study area and for similar villages that wish to carry out rural environment improvements. It will also help to deepen the study of rural environment improvement and could provide a reference basis for solving rural environmental problems in the new period.

## 2. Overview of the Study Area and Data Sources

### *2.1. Overview of the Study Area*

Shangluo (33°2′ N~34°24′ N, 108°34′ E~111°1′ E) is located at the southern foot of the Qinling Mountains in eastern Shaanxi Province, with a high terrain in the northwest and a low terrain in the southeast, bordering the provinces of Henan and Hubei, spanning

two major river basins, the Yangtze River and the Yellow River, and including Shangzhou, Luonan, Shanyang, Danfeng, Shangnan, Zhenan, and Zhashui. The study area is shown in Figure 1. According to the 2022 Shangluo City National Economic and Social Development Statistics Bulletin, the city has a total of 862,600 households, a household population of 2,479,700, a resident population of 2,020,600, and a resident population urbanization rate of 49.98%. Shaanxi Province has named provincial beautiful and livable model villages five times, and, to date, a total of 62 villages (communities) in Shangluo City have been awarded this title. In recent years, the Shangluo Human Settlement Office has issued the Rural Human Settlement Environment Improvement Initiative to promote further improvements in rural human settlements. To this end, it has explored the implementation of the rural living waste management model: "household classification, village collection, township transportation, county, and district treatment". As its focus, it selected toilet renovation, classifying and advancing the "toilet revolution" through a whole village demonstration. This precipitated a boom in the city's rural environment improvement work.

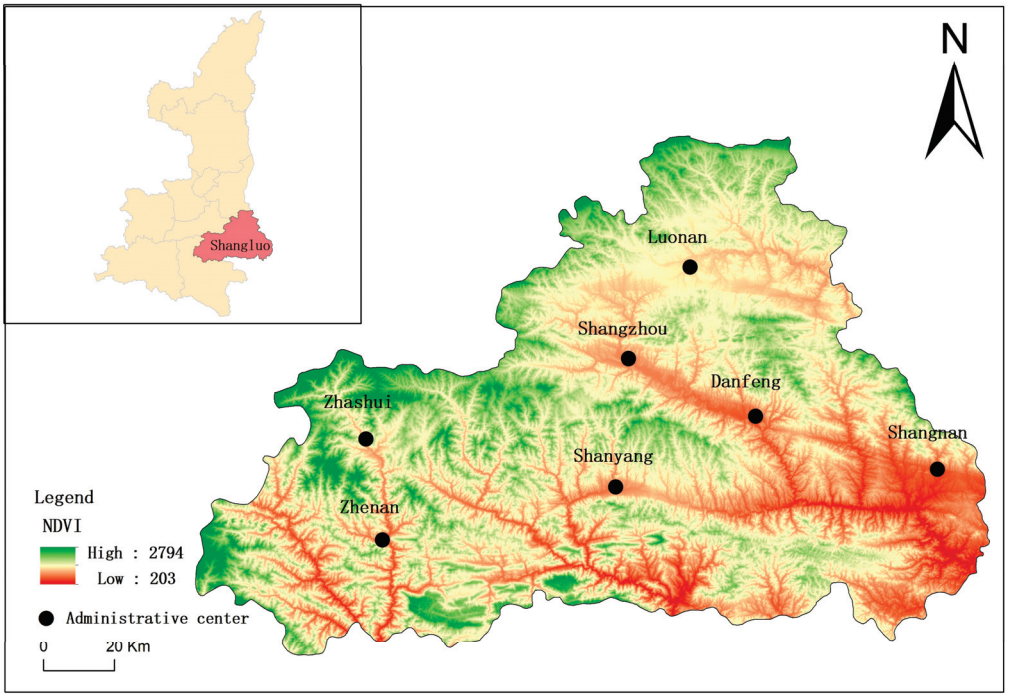



**Figure 1.** The study area.

### *2.2. Data Sources*

The data were obtained from multiple rounds of field research and household interviews. These were conducted by the research group in Shangluo City in July 2022, and in January and August 2023. These data were supplemented by secondary information that was provided by the county government, the Habitat Office, and other departments. These data mainly included statistical information about counties and districts, and government statistical bulletins. To comprehensively understand the overall situation of the rural environment in Shangluo City, this study adopted a combination of stratified sampling and random sampling to determine the sample villages. The specific sampling process was as follows: three counties were randomly selected from among the seven counties of Shangluo City, two townships in each sample county were selected, two administrative villages were randomly selected in each township, and 12 sample villages were selected in total. Simple random sampling was conducted according to the list of villagers at home, which was provided by the village committee, and 10–15 households were selected for the household survey in each sample village. The survey was conducted among family members who were aware of the environment of the village: the head of the household responded to

the questionnaire and their response was recorded by the surveyor. A total of 152 questionnaires were distributed and 150 valid questionnaires were recovered, with an effective rate of 98.68%. The questionnaires included the following: (1) basic information about the farmers (gender, age, employment, education level, etc.) and (2) the status of the rural environment (infrastructure, household sewage treatment, toilet renovation, household waste treatment, and construction and management mechanisms) (Appendix A).

## 3. Research Methodology

### *3.1. Construction of Rural Environmental Quality Evaluation Index System*

This study's methodology was based on the objectives and tasks referenced in the Five-Year Action Program for Improving and Upgrading Rural Human Settlement Environment in Shaanxi Province (2021–2025). It was also people-oriented and followed the basic principles of scientificity, objectivity, comprehensiveness, and ecological priority. In addition, it took into account the actual situation of the rural environment in Shangluo City through repeated field surveys, household interviews, and consultations with relevant experts in rural environments. In this way, a system of evaluation indicators for the rural environmental quality in Shangluo City was constructed, with 16 indicators across five systems finally being identified (Table 1).

**Table 1.** Evaluation index system for the rural environmental quality in Shangluo City.

| Target Layer (A) | System Layer (B) | Indicator Layer (C) |
|---|---|---|
| The rural environmental quality evaluation in Shangluo City (A) | Infrastructure (B1) | Road leveling condition (C1) |
| | | Greening of the village (C2) |
| | | Condition of public lighting facilities (C3) |
| | | Residential housing situation (C4) |
| | Household sewage treatment (B2) | Household sewage discharge pattern (C5) |
| | | Management of black, foul-smelling water bodies (C6) |
| | Toilet renovation (B3) | Rural sanitary latrine penetration rate (C7) |
| | | Satisfaction of farmers with latrine conversion (C8) |
| | | Toilet feces disposal methods (C9) |
| | Household waste treatment (B4) | Household waste classification situation (C10) |
| | | Household waste removal frequency (C11) |
| | | Household waste disposal methods (C12) |
| | Construction and management mechanisms (B5) | Farmer recognition (C13) |
| | | Farmer participation (C14) |
| | | Publicity for environmental remediation (C15) |
| | | Environmental remediation actions (C16) |

(1) Infrastructure

Infrastructure indicators included the leveling of roads, the greening of villages, public lighting facilities, and residential housing. The leveling of roads in a village reflects the quality of transportation within it, which, thus, reflects the accessibility of travel for the villagers. The greening of a village was shown by the fruits, vegetables, flowers, and trees planted in front of and behind the farmers' houses, as well as by the reuse of wasteland, abandoned land, and marginal land. The public lighting facilities were characterized by the coverage and spacing of the streetlights within the village. The residential housing was characterized by the types of houses and their degree of dilapidation, thus reflecting the living conditions of the villagers.

(2) Household Sewage Treatment

Household sewage treatment indicators included the way that household sewage is discharged and the management of black, foul-smelling water bodies. The way that household sewage is discharged was mainly manifested in four ways: centralized treatment and discharge, discharge into sewers, discharge into nearby ditches, and random discharge.

The management of black, foul-smelling water bodies was characterized by the number of them in front of and behind houses; these included rivers, ponds, and ditches.

(3) Toilet Renovation

Toilet renovation indicators included the penetration rate of sanitary latrines in farm households, the satisfaction of farm households with their latrine renovation, and the toilet feces disposal method. The prevalence of sanitary latrines in farm households was characterized by the extent to which sanitary latrines had been installed in village households' yards or rooms; the satisfaction of farmers with their latrine conversion was characterized by the degree of their satisfaction with how sanitary this was; and how the toilet feces disposal method was handled was mainly manifested in how they were discharged into the sewage network: burying them directly in a pool of wastewater, independently transporting them to the field for use as organic fertilizer, or discharging them directly and untreated.

(4) Household Waste Treatment

Household waste treatment indicators included the classification of household waste, the frequency of household waste removal, and the method of household waste disposal. The classification of household waste was characterized by farmers' knowledge of household waste classification. The frequency of household waste removal was characterized by the speed of cleaning and transferring household waste in the village. The method of handling household waste was mainly manifested in how it is transferred to the waste disposal stations: storing it in designated places, centralized incineration, or throwing it away at random.

(5) Construction and Management Mechanisms

Construction and management mechanism indicators included the degree of recognition by farmers, the degree of farmers' participation, the publicity of environmental improvement, and the action taken on environmental improvement. Farmer recognition was characterized by the farmers' degree of satisfaction with the improvement of the rural human settlement environment in their villages, and farmer participation was characterized by their enthusiasm for these improvements. Environmental improvement publicity was characterized by the frequency of the government's environmental publicity work in their villages. Environmental improvement action was mainly manifested in the multi-dimensional co-management of the government, the community, enterprises, and the villagers.

### *3.2. Analytic Hierarchy Process*

The analytic hierarchy process was a comprehensive and subjective judgment, which was achieved through the qualitative data and quantitative analysis of a combination of methods, and by comparing the importance of the two factors to achieve the relative importance of the indicators between the weights [25]. According to the constructed evaluation index system of the rural environmental quality in Shangluo City and using the analytic hierarchy process, 10 experts in the field were invited to score the indexes uniformly. They assigned values according to the degree of their importance.

The maximum feature root was calculated according to the constructed judgment matrix of the weight relationship among all levels of indicators. The consistency indicator (CI) value, the ratio indicator (RI) value, and the consistency ratio (CR) value were determined. The consistency test was then conducted, and the weight was calculated. Finally, the weight value of the rural environmental quality evaluation index of Shangluo City was obtained (Table 2).

**Table 2.** The weights and scores of the rural environmental quality evaluation index in Shangluo City.

| Target Layer | System Layer | Weight | Score | Indicator Layer | Weight | Scores |
|---|---|---|---|---|---|---|
| The evaluation of rural environmental quality in Shangluo City (A) | Infrastructure (B1) | 0.0556 | 2.993 | Road leveling condition (C1) | 0.0748 | 2.886 |
| | | | | Greening of the village (C2) | 0.4705 | 3.013 |
| | | | | Condition of public lighting facilities (C3) | 0.273 | 3.033 |
| | | | | Residential housing situation (C4) | 0.1817 | 2.927 |
| | Household sewage treatment (B2) | 0.1804 | 2.614 | Household sewage discharge pattern (C5) | 0.207 | 2.967 |
| | Toilet renovation (B3) | 0.1034 | 3.038 | Management of black, foul-smelling water bodies (C6) | 0.793 | 2.521 |
| | | | | Rural sanitary latrine penetration rate (C7) | 0.0887 | 3.027 |
| | | | | Satisfaction of farmers with latrine conversion (C8) | 0.6813 | 3.039 |
| | | | | Toilet feces disposal methods (C9) | 0.23 | 3.046 |
| | Household waste management (B4) | 0.2178 | 2.811 | Household waste classification situation (C10) | 0.6257 | 3.02 |
| | | | | Household waste removal frequency (C11) | 0.281 | 2.333 |
| | | | | Household waste disposal methods (C12) | 0.0933 | 2.828 |
| | Construction and management mechanisms (B5) | 0.4428 | 2.693 | Farmer recognition (C13) | 0.077 | 2.861 |
| | | | | Farmer participation (C14) | 0.25 | 2.672 |
| | | | | Publicity for environmental remediation (C15) | 0.156 | 2.727 |
| | | | | Environmental remediation actions (C16) | 0.517 | 2.668 |

The formula for the maximum characteristic root ($\lambda_{max}$) is as follows:

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(BW)_i}{nW_i} \quad (1)$$

$B$ represents the judgment matrix of each index, $W$ represents the weight of each index, $n$ represents the order of the judgment matrix count, and $i$ = 1, 2, . . ., $n$.

The formula for the $CI$ is as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

The formula for the $CR$ is as follows:

$$CR = \frac{CI}{RI} \quad (3)$$

### *3.3. Fuzzy Comprehensive Evaluation Method*

The fuzzy comprehensive evaluation method is an evaluation method that transforms the qualitative evaluation into a quantitative evaluation. It made an overall evaluation of the research object [26]. The steps for evaluating the rural environmental quality in Shangluo City are outlined in the sections below.

#### 3.3.1. Establishing Factor Sets and Evaluation Sets

In the evaluation index system, factor set U was established first: the first layer was U1 (the rural environmental quality in Shangluo City); the second layer was U2 (infrastructure, household sewage treatment, toilet renovation, household waste treatment, and construction and management mechanisms); and the third layer was U3, which was made up of 16 evaluation factors, such as the road leveling condition. Second, evaluation set V was established, which was set into four levels: V1, V2, V3, and V4. They were assigned ranks of 1, 2, 3, and 4 points, respectively.

#### 3.3.2. Constructing a Fuzzy Judgment Matrix

According to the ith factor of factor set U, the affiliation degree of Ui to the jth element, Vj, in the evaluation set V was Rij. The evaluation set of the ith factor was Ri = [Ri1, Ri2, Ri3,..., Rim] (i = 1, 2,..., n). For the comprehensive analysis and evaluation of the n factors,

there were n fuzzy evaluation sets: R1, R2, . . ., Rn. The matrix, R, combined by them was the fuzzy relationship matrix [27]; see Formula (4) below.

$$R = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_m \end{bmatrix} = \begin{bmatrix} r_{11} r_{12} \cdots r_{1n} \\ r_{21} r_{22} \cdots r_{2n} \\ \vdots\vdots\vdots \\ r_{m1} r_{m2} \cdots r_{mn} \end{bmatrix} \quad (4)$$

3.3.3. Performing Fuzzy Integrated Evaluation Operations

The evaluation matrix, R, and the weights of the indicators, W, were calculated using the following formula:

$$B = W_i \cdot R_I = W_i \cdot \begin{bmatrix} R_{11} R_{12} \cdots R_{1n} \\ R_{21} R_{22} \cdots R_{2n} \\ \vdots\vdots\vdots \\ R_{m1} R_{m2} \cdots R_{mn} \end{bmatrix} \quad (5)$$

## 4. Results and Analysis

### *4.1. Evaluation Results for Rural Environmental Quality*

The weight of each index was calculated according to the analytic hierarchy process, and the score for each index was calculated using the fuzzy comprehensive evaluation method. Finally, through this, the scores of each system and index layer in the rural environment of Shangluo City were obtained (Table 2).

The comprehensive evaluation score, B, of the rural environmental quality in Shangluo City was 2.757, which is a good level. The rural environmental quality evaluation table for Shangluo City is shown in Table 3. The effect evaluation values of the infrastructure, household sewage treatment, toilet renovation, household waste treatment, and construction and management mechanisms in the system layer were 2.993, 2.614, 3.038, 2.811, and 2.693, respectively. The toilet renovation scored the highest, and the household sewage treatment and construction management mechanisms scored the lowest. Five out of sixteen items in the indicator layer were lower than the comprehensive evaluation indicators: the management of black, foul-smelling water bodies, the frequency of household waste removal, the participation of farmers, the environmental clean-up publicity, and the action on environmental remediation.

**Table 3.** The rural environmental quality evaluation table for Shangluo City.

| Scores | (0,1) | (1,2) | (2,3) | (3,4) |
|---|---|---|---|---|
| Rating levels | Unqualified | Qualified | Good | Excellent |

The evaluation score for the level of toilet renovation was 3.038, which was the highest evaluation score among the five components at the system layer. The evaluation values for the sanitary rural latrine penetration rate, farmers' satisfaction with latrine conversion, and latrine fecal waste treatment methods in the second-level indicators were 3.027, 3.039, and 3.046, respectively. These values were higher than those of the comprehensive evaluation indicators. According to the statistical bulletin, Shangluo City has constructed 65,500 rural household toilets and 836 rural public toilets, and the penetration rate of the sanitary rural toilets has reached 72.9%. From the actual research, we know that farmers are more satisfied with the change from "dry latrines" to "flush toilets" and pay more attention to the cleanliness and safety of the toilets and the availability of facilities. The fecal matter from the toilets in the villages is centrally discharged to the sewage network for unified treatment or is independently transported to the fields and used as organic fertilizer. These methods ensure that fecal matter from the toilets and the use of resources do not harm the

quality of the rural environment. This further confirms the positive role played by toilet renovation in promoting the improvement of rural environmental quality [28].

In terms of infrastructure, the evaluation score was 2.993, ranking second. The indicator layers of road leveling, village greening, the condition of the public facilities, and residential housing in the indicator layer were 2.886, 3.013, 3.033, and 2.927, respectively, which were all higher than the comprehensive evaluation index. In recent years, Shangluo City has focused on creating provincial-level demonstration villages for "Four Good Rural Roads". These focus on "two links" and realize the following goal: 100% of the established villages are connected to hardened roads, buses, and postal routes, forming a rural transportation network that is "safe and convenient". Village cadres have led the villagers in continuing the following actions: village cleaning and landscaping; increasing the greening efforts (in the front and back of the house and in front of the courtyards); the construction of small/micro parks and public green space, which mainly manifested as planting flowers and trees; painting a "publicity wall"; and other rectification actions. Local governments have promoted the integration of public lighting facilities and roads in the villages by strengthening the construction of street lamps on the main roads in the villages, planning the spacing of street lamps, and improving the public service facilities in rural areas. The state has taken a variety of measures to ensure the safety of rural housing, thus removing the hidden safety hazards of farmers' housing: carrying out special safety rectifications of self-built houses, carrying out the unified demolition of dangerous and abandoned houses, and reasonably resettling low-income rural groups and other key targets to migrant relocation houses.

At the level of household waste management, the evaluation score was 2.811, which was slightly higher than the comprehensive evaluation score. The evaluation scores for the secondary indicators—the classification of household waste, the frequency of household waste removal, and the household waste treatment method—were 3.02, 2.333, and 2.828, respectively. The score for the frequency of household waste removal was lower than the comprehensive evaluation score. Rural household waste management is a key project in rural environmental improvement. It is also the foundation for realizing rural revitalization and for building livable, workable, and beautiful villages. With the development of recreation and tourist facilities in villages, rural inns and lodgings have grown, meaning that household waste has gradually increased. The government has carried out special rural garbage management actions: it has explained garbage classifications and the harmless treatment of garbage to villagers, and has installed garbage classification barrels and garbage removal vehicles, etc., in villages. However, these efforts have been negatively affected by the villagers' living habits and the fact that their awareness of environmental protection is still relatively limited. This has resulted in garbage piling up and being left unattended at the treatment stations. In addition, the vast majority of villages are located in mountainous areas, where the distance between them is relatively long and the speed of waste removal is relatively slow, meaning that household waste management is still a serious issue.

At the level of construction and management mechanisms, the evaluation score was 2.693, and the evaluation scores of the secondary indicators—the recognition of farmers, farmers' participation, the publicity on environmental remediation, and action on environmental remediation—were 2.861, 2.672, 2.727, and 2.668, respectively. The scores were lower than the comprehensive evaluation scores, with the exception of the recognition of farmers. To effectively consolidate the results of rural environment improvement and to create clean, tidy, beautiful, and livable rural landscapes, Shangluo City's governments at all levels have carried out in-depth rural environment improvement work and have driven key projects forward, such as village appearance, living waste management, toilet renovation, and household sewage management. Farmers are more satisfied with the current rural environment improvements, but they still might not realize that they are participants in and the main force behind the rural environment improvement work. They are still "waiting, relying and wanting"—they tend to be overly reliant on the power of

the government or on village committees and other third parties, and they tend to have little enthusiasm for participating in the process of rural environment improvement. Due to the distance between the villages and the generally low education levels among the villagers, the government's ability to publicize environmental protection and to educate the villagers is limited to the distribution of environmental protection pamphlets, hanging banners and signboards, and publicity trucks. This is having poor results. The majority of the households interviewed in this study were headed by middle-aged people, who rely on farming at home and working outside the home to support their families' expenditures. Their initiative to consciously participate in the improvement of the rural environment is relatively limited, and they tend to rely on the government's financial support and the village committees to take the lead in the management of their environment.

The evaluation score for household sewage treatment was 2.614, which was the lowest score in the target layer, and the evaluation scores of its secondary indicators—the household sewage discharge pattern and the treatment of black, foul-smelling water bodies—were 2.967 and 2.521, respectively. The scores for the treatment of black, foul-smelling water bodies were lower than the comprehensive evaluation scores. The sewage treatment rate for rural households in Shangluo City is still only 41.07%, which makes it the biggest obstacle to improving the quality of the rural environment. To ensure that sewage treatment is effective, all levels of government in Shangluo City have built sewage treatment facilities in the villages and put them into use, which can be seen through the construction of sewage treatment stations, the laying of sewage pipe networks, the regular operational supervision of each site, guiding farmers to discharge their household sewage hygienically, and continuously improving the effectiveness of sewage treatment. Farmers in Shangluo City mainly focus on planting; therefore, they use chemical fertilizers, pesticides, and other chemical substances in agricultural production. These chemicals are then picked up in rainwater flows, meaning that they end up in rivers and ditches, which destroys the ecological balance of the water bodies. This is compounded by the industrial wastewater generated by the numerous factories in the villages, which also pollutes the water. These sources of pollution culminate in black, foul-smelling water bodies [29]. Despite continued efforts across Shangluo City to carry out river waste treatment and to comprehensively clean up the residual malodorous ditches in the river, the impact of these efforts on the management of black, foul-smelling water bodies is still not obvious.

### *4.2. Countermeasures to Improve Rural Environmental Quality*

By analyzing the differences in the scores for importance and satisfaction among the indicators, this study can help decision makers to judge the strengths and weaknesses of each indicator. The average score for importance (0.3125) and the average score for satisfaction (2.848) among the 16 indicators were used as the dividing line to plot the IPA quadrant. The range of the importance scores was 0–0.8 and the range of the satisfaction scores was 2.3–3.1, as shown in Figure 2.

The first quadrant is the dominant area, reflecting the three indicators to which the villagers attached high importance and satisfaction: greening in the village (C2), satisfaction with the conversion of latrines in farm households (C8), and the classification of household waste (C10). In the follow-up process for rural environment improvement in Shangluo City, the village cadres encouraged the villagers to fully revitalize the unused land in the courtyard by turning it into tree gardens, orchards, gardens, or vegetable gardens; to make use of the deserted vacant land in front of and behind their houses; and to continue greening and beautification actions across the villages. The concept of "small toilet, big livelihood" was set up at a country level. It fully respects the wishes of farmers by starting from their actual needs, thus improving their satisfaction with the toilet improvements implemented. Government staff regularly carry out publicity activities on household garbage classification, explaining garbage classification to enhance farmers' awareness of environmental protection and to encourage them to develop good habits.

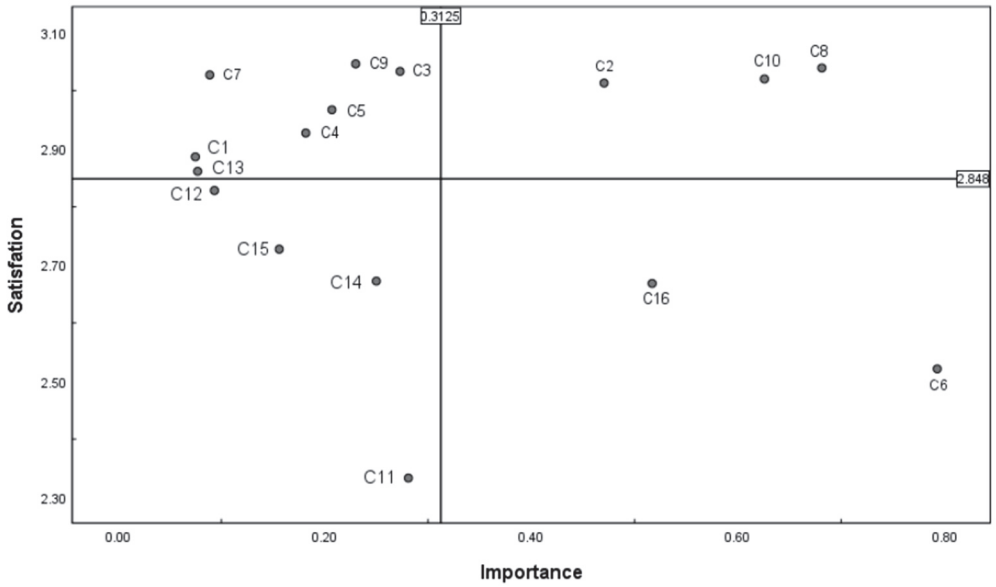



**Figure 2.** Importance–satisfaction IPA quadrant chart.

The second quadrant is the maintenance area, reflecting the seven indicators to which the villagers attached low importance and high satisfaction: road leveling (C1), the lighting of public facilities (C3), living houses (C4), household sewage discharge (C5), sanitary rural latrine prevalence rate (C7), toilet feces disposal methods (C9), and farmers' recognition (C13). These indicators are concentrated in the two system layers of infrastructure and toilet renovation, which represent the key projects of rural environmental quality improvement in Shangluo City. In the future, the construction of infrastructure should be continuously improved, and long-term management and protection mechanisms should be established. The government should continue to take a leading role in ensuring that the farmers are the participants, builders, and beneficiaries in toilet conversion, and they should actively listen to the views of the villagers to ensure that the toilet renovation program is in line with reality.

The third quadrant is the expansion area, reflecting the four indicators to which the villagers attached low importance and satisfaction: the frequency of household waste removal (C11), household waste disposal methods (C12), the participation of farmers (C14), and the publicity of environmental clean-up (C15). These indicators were mainly focused on the two governance levels of household waste management and construction management mechanisms and represent projects that have not yet been prioritized or have not attracted the attention of the villagers themselves. Going forward, sufficient elastic space should be left for projects such as farmers' participation and the publicity of environmental remediation, which should not be regarded as the focus of current construction. However, in the future development and construction of Shangluo City, the government should pay attention to these projects dynamically, so that, in time, the demands in the construction process can be supplemented. Projects such as household waste removal frequency and methods of household waste disposal are very important in the process of rural environment construction; however, not enough attention has been given to them due to the awareness level of the villagers. Follow-up village cadres need to strengthen publicity, education, and behavior guidance so that the villagers can actively participate in the construction and maintenance of their hometown environments.

The fourth quadrant is the repair area, which reflects the two indicators to which the villages attached high importance but low satisfaction: the management of black, foul-smelling water bodies (C6) and action on environmental remediation (C16). Villagers expressed a high degree of expectation for the indicators in this area, but the actual result has not been satisfactory. Going forward, the village cadres should organize the villagers to investigate the black and malodorous water bodies in the village, and they should regularly

count them. The government has invited experts to analyze the characteristics of different types of black, foul-smelling water bodies—such as rivers, pits, and ditches—and fully analyzed their characteristics and causes, based on the local natural environment and economic development level [30]. Going forward, the government should also classify and treat agricultural wastewater and farmers' domestic sewage, choosing reasonable physical, chemical, and biological methods [31]. Village officials should also encourage villagers to actively participate in the treatment of black, foul-smelling water bodies, and should improve the long-term supervision mechanisms to ensure the effectiveness of the treatment. Rural environmental improvement work requires the construction of a set of multi-dimensional, long-term management and care mechanisms which should be based on government investment and then supplemented by farmers' support and the active participation in social capital: First, as farmers are the direct beneficiaries of rural environmental improvement, they should play the main role in rural environmental construction. Village cadres should actively guide party members to participate in environmental governance and incorporate rural environmental remediation into village rules and regulations to enhance farmers' awareness of consciously protecting the environment [32]. Second, rural environment improvement needs national capital investment. The government should allocate reasonable funds, not only for key areas of equipment procurement or for technology research and development, but also for technical training and incentives to encourage farmers to participate in environmental governance [33]. In addition, social capital can be used to participate in rural environmental governance through corporate sponsorship, and it can also make use of advanced management means and technological advantages to improve rural environmental quality [34].

## 5. Discussion

Against the background of rural revitalization, this study constructed a set of rural environmental quality evaluation index systems for the environmental characteristics of Shangluo City and the laws on rural development and construction. In this study, we also put forward countermeasures to improve rural environmental quality in a targeted manner. The evaluation results of this study reflect the basic situation of the rural environment in Shangluo City, and the evaluation results were consistent with the actual situation. To a certain extent, this can provide a reference for the next phase of rural environment improvement work in Shaanxi Province. This study has expanded the research field of rural environmental evaluation and has filled the gap in the existing literature on rural environmental evaluation in Shangluo City. However, it must be recognized that the indicator system proposed in this study may have limitations and be incomplete. For example, rural ecosystem indicators, such as fertilizer use and forest cover, were not addressed [35]. Moreover, the research data are of a regional and time-dependent nature; therefore, the exploration is only relevant to some villages in Shangluo City. This may lead to the research results not being universally applicable.

Rural environmental remediation work is a long-term, systematic project, which is variable and complex. In future studies, scholars could further expand the scope of this research by combining the disciplinary knowledge of ecology, geography, and urban and rural planning [36,37]. They should also adopt emerging research tools such as 3S technology and big data analysis [38]. The evaluation index should also be further revised according to the regional characteristics through the regular evaluation method and the long-term management mechanisms that are established [39].

## 6. Conclusions

First, this study constructed a set of rural environmental quality evaluation index systems. Next, a hierarchical analysis was used to determine the index weight, and the index score was calculated using the fuzzy comprehensive evaluation method. Finally, based on the IPA quadrant map, targeted countermeasures to improve the rural environmental

quality of Shangluo City were proposed. This study's conclusions can be summarized as follows:

(1) In this study, sixteen indicators were selected from across five aspects to evaluate the overall rural environmental quality in Shangluo City. The results showed that the rural environmental quality of Shangluo City is adequate.
(2) According to the evaluation results, the scores for household sewage treatment and for the construction and management mechanisms in the system layer were relatively low. The scores for the treatment of black, foul-smelling water bodies, the frequency of household waste removal and transportation, the participation of farmers, the publicity on environmental remediation, and the action on environmental remediation were lower than the comprehensive evaluation scores.
(3) Based on the IPA quadrant map, the 16 indicators were divided into four quadrants according to the degree of importance and satisfaction expressed by the villagers. The results show that the villagers attached high importance to the treatment and management of black, foul-smelling water bodies and to action on environmental remediation; however, their satisfaction with these indicators was low. In the future, the Shangluo Government should prioritize the farmers' participation in the treatment of black, foul-smelling water bodies and environmental remediation in the improvement of rural environmental quality and rural environmental construction.

**Author Contributions:** C.L. contributed to the conception of this study; Q.L. undertook the main actions in this study; and Z.Z. and Y.F. contributed significantly to the analysis and manuscript preparation. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Shaanxi Natural Science Basic Research Program (grant number 2023-JC-QN-0803); the Key Scientific Research Program of the Shaanxi Provincial Department of Education (22JT019); the Humanities and Social Science Research General Project of the Ministry of Education (23YJC630076); and the National Social Science Foundation of China (22BJY206).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Acknowledgments:** The authors sincerely thank the editor and anonymous reviewers for their valuable comments and suggestions for improving the quality of this paper.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Appendix A. Questionnaire on Rural Environmental Quality in Shangluo City

Part I. Basic information about the farmers.
1. What is your gender?
(1) Male
(2) Female
2. What is your age?
(1) 18–25 years old
(2) 26–35 years old
(3) 36–45 years old
(4) 46–60 years old
(5) 60 years old and above
3. What is your level of education?
(1) Elementary school and below
(2) Junior high school
(3) High school
(4) Junior college
(5) Bachelor's degree and above

4. What is your current occupation?
(1) Farming at home
(2) Farming and working
(3) Working outside the home
(4) Other
Part II. The situation of the rural environment
I. Infrastructure
5. What is your assessment of the current leveling of roads in your village?
(1) Roads are very flat
(2) Roads have less breakage
(3) Roads have lots of breakage
(4) Roads have many potholes
6. What is your assessment of the greening in your village?
(1) Very satisfied
(2) Satisfied
(3) Basically satisfied
(4) Dissatisfaction
7. What is your assessment of the public lighting facilities in your village?
(1) Roads are well-equipped with public lights.
(2) The distance between the public lights is far away.
(3) The public lights are damaged.
(4) Roads aren't well-equipped with public lights.
8. What is your assessment of your current housing situation?
(1) Very satisfied
(2) Satisfied
(3) Basically satisfied
(4) Dissatisfaction
II. Household sewage treatment
9. What is your assessment of the household sewage treatment from your home?
(1) Household sewage treatment is discharged into the sewage treatment plant for centralized treatment and unified discharge.
(2) Household sewage treatment is discharged into the sewers.
(3) Household sewage is discharged into the nearby ditches.
(4) Household sewage is discharged anywhere.
10. What is your assessment of the management of black-smelling water bodies in your village?
(1) No black-smelling water bodies
(2)A small amount of black-smelling water bodies
(3) A large amount of black-smelling water bodies
(4) Black-smelling water bodies are always in the river
III. Toilet renovation
11. What is your assessment of the penetration rate of sanitary latrines in your village?
(1) There are public toilets in the village.
(2) Villagers have flush toilets in their homes.
(3) Villagers have dry pit latrines in their homes.
(4) No toilet
12. How satisfied are you with the latrine conversion?
(1) Very satisfied
(2) Satisfied
(3) Basically satisfied
(4) Dissatisfaction

13.How do you usually do with the toilet feces?
(1) Discharge to sewerage network
(2) Direct burial of fecal lagoons
(3) Self-transported to the field for organic fertilizer
(4) Discharge without treatment
IV. Household waste management
14. How is the classification of household waste in your village?
(1) There are special staff in the village to classify the waste
(2) There are waste sorting buckets in the village
(3) Waste sorted randomly
(4) No waste classification
15. What is the frequency of household waste removal in your village?
(1) Clean once a day
(2) Clean every two days
(3) Clean once every three days or more
(4) Nobody clean
16. How is household waste disposed of in your village?
(1) Transfer Transfer waste disposal station
(2) Unified storage in the designated locations
(3) Discarded randomly
(4) Centralized burning
V. Construction and management mechanisms
17. How satisfied are you with the rural environment?
(1) Very satisfied
(2) Satisfied
(3) Basically satisfied
(4) Dissatisfaction
18. How is your enthusiasm to participate in the rural environment?
(1) Active participation
(2) Occasional participation
(3) Support but not participate
(4) Never participated
19. How does Environmental clean-up publicity work in your village?
(1) Always publicity
(2) Regular publicity
(3) Occasional publicity
(4) Never publicity
20. What actions do you think need to be taken to improve the rural environment?
(1) Government Funding
(2) Social organization manpower inputs
(3) Farmers' participation in conservation
(4) No action taken

## References

1. Wu, L.Y. *Introduction to Sciences of Human Settlements*; China Architecture & Building Press: Beijing, China, 2001; pp. 97–112.
2. Woods, M. Engaging the global countryside: Globalization, hybridity and the reconstitution of rural place. *Prog. Hum. Geogr.* **2007**, *31*, 485–507. [CrossRef]
3. Li, D.Q.; Hou, L.L.; Min, S.; Huang, J.K. The effects of rural living environment improvement programs: Evidence from a household survey in 7 provinces of China. *Manag. World* **2021**, *10*, 182–194.
4. Doxiadis, C.A. Action for human settlements. *Ekistics* **1975**, *40*, 405–448.
5. Li, H.B.; Zhang, X.L. A review and trend on rural settlement geography abroad. *Hum. Geogr.* **2012**, *27*, 103–108.
6. Lewis, C.A.; Mrara, A.Z. Rural settlements, mission settlements and rehabilitation in Transkei. *Geojournal* **1986**, *12*, 375–386. [CrossRef]
7. Buscema, M.; Diappi, L.; Ottanà, M. A neural network investigation of the crucial facets of urban sustainability. *Subst. Use Misuse* **1998**, *33*, 793–817. [CrossRef] [PubMed]

8. Zhang, J.; Sun, R.R.; He, Y.B. Analysis on the knowledge graph of international rural human settlements research. *Resour. Dev. Mark.* **2022**, *38*, 679–687+738.
9. Carrión, J.S.; Fuentes, N.; González-Sampériz, P.; Quirante, L.S.; Finlayson, J.C.; Fernández, S.; Andrade, A. Holocene environmental change in a montane region of southern Europe with a long history of human settlement. *Quat. Sci. Rev.* **2007**, *26*, 1455–1475. [CrossRef]
10. Fidler, D.; Olson, R.; Bezold, C. Evaluating a long-term livable communities strategy in the US. *Futures* **2011**, *43*, 690–696. [CrossRef]
11. De Castro, C.; Mediavilla, M.; Miguel, L.J.; Frechoso, F. Global solar electric potential: A review of their technical and sustainable limits. *Renew. Sust. Energy Rev.* **2013**, *28*, 824–835. [CrossRef]
12. Qu, Y.C.; Zhao, G.J. Policy circumvention and its correction in rural habitat improvement. *Theory Guide* **2023**, *7*, 81–86. (In Chinese)
13. Zhang, H.J.; Xue, G.X. Changes of policies in relation to rural human settlement environment governance in China: Characteristics and evolution. *J. Arid Land Resour. Environ.* **2022**, *36*, 8–15.
14. Xu, S.Q.; Yun, Y.T.; He, J. Analysis on the Current Situation and Improving Countermeasures of Rural Living Environment. *Environ. Prot.* **2018**, *46*, 44–48.
15. Yu, F.W.; Hao, X.B. Research status and prospect of rural human settlement environment renovation. *Ecol. Econ.* **2019**, *35*, 166–170.
16. Zhu, W.T.; Luan, J.D. Influencing factors and multiple realization paths of farmers' satisfaction with the improvement of rural living envieonment: Based on FSQCA method. *J. Chin. Agric. Mech.* **2022**, *43*, 231–238.
17. Guo, X. Optimization path of rural human settlement environment improvementin Liaoning province under rural revitalization strategy. *Agric. Econ.* **2023**, *12*, 62–63. (In Chinese)
18. Lu, R.L.; Xu, Z.Q. Model forgeneration of rural living environments governance performance: A fuzzy set qualitatively comparative analysis. *J. Arid Land Resour. Environ.* **2023**, *37*, 1–12.
19. Xi, H.; Zhu, Y.T. Study on evaluation and optimization of rural ecological human settlements environment in Northwest Sichuan. *Resour. Dev. Mark.* **2023**, *39*, 164–169.
20. Han, Z.; Peng, C.; Liu, H.G. Government Guarantee, Social Supervision and Rural Residents' Behavior of Centralized Disposal of household Waste—Analysis Based on the Survey Data of 1365 Farmers' Households in 183 Villages. *Rural. Econ.* **2023**, *10*, 73–82. (In Chinese)
21. Wang, Y.F.; Li, T.T.; Meng, X.T. Evaluation of China's rural human settlements quality and its spatiotemporal change characteristics from 2010 to 2020. *Geogr. Res.* **2022**, *41*, 3245–3258.
22. Lu, Q. Construction and Empirical Evidence of Comprehensive Evaluation Indicator System for Rural Habitat Environment--Taking Hubei Province as an Example. *Stat. Decis. Making* **2022**, *38*, 71–75. (In Chinese)
23. Gao, H.; Jin, J.S.; Li, F.; Zhou, C. Evaluation and development strategy of provincial rural human settlement construction in China. *J. Ecol. Rural. Environ.* **2015**, *31*, 835–843.
24. Liu, B.T.; Zhang, J.R.; Yang, C.; Dong, J.H. Quality assessment on rural construction of human settlements in loess plateau. *J. Lanzhou Univ. Technol.* **2023**, *49*, 117. (In Chinese)
25. Yu, J.; Chen, W.J.; Wang, H.; Gan, L.; Zhang, S.T. Application of the analysis hierarchical process in establishing the weight values of PACS score system. *China Med. Equip.* **2013**, *28*, 44–47. (In Chinese)
26. Dong, Y.H.; Zhang, X.Y.; Zhang, X.Y.; Li, L. Evaluation of farmland non-point source pollution control technology in Liao River based on AHP-FCE method. *Environ. Eng.* **2023**, *41*, 150–157.
27. Wang, J.Y.; Zong, X.Y.; Wang, D.Y. Study on Evaluation of Implementation Effect of International Standards of Traditional Chinese Medicine Based on AHP-Fuzzy Comprehensive Evaluation Method. *J. Basic Chin. Med.* **2023**, *29*, 770–774.
28. Du, J. Formation logic and solution path of inappropriate expansion of government responsibilities in the construction of service-oriented government at the grassroots level: A case study on the government's promotion of rural toilet renovation projects. *China's Rural. Econ.* **2023**, *2*, 168–184. (In Chinese)
29. Qin, X.; Chen, Z.S.; Zhou, H.; Wen, G.H. Spatio-temporal characteristics of agricultural non-point source pollution and its decoupling relationship with grain production in Hunan Province. *Res. Agric. Mod.* **2023**, *44*, 540–549.
30. Cui, Y.Z.; Jia, X.M.; Huang, Y.J.; Liu, H.D. Current Situation, Problems and Countermeasures of Black and Odorous Water Treatment in Rural Areas. *China Environ. Manag.* **2022**, *14*, 54–59. (In Chinese)
31. Xu, W.; Wang, W.; Deng, B.; Liu, Q. A review of the formation conditions and assessment methods of black and odorous water. *Environ. Monit. Assess.* **2024**, *196*, 42. [CrossRef]
32. Zhao, X.M.; Jiang, W.; Cheng, W.M. Study on the Willingness of Rural Residents to Participate in the Environmental Governance of Human Settlements Based on the Theory of Planned Behavior: Taking Xinjiang as an Example. *J. Ecol. Rural. Environ.* **2021**, *37*, 439–447. (In Chinese)
33. Dong, H.; Zhang, Y.; Chen, T. A study on farmers' participation in environmental protection in the context of rural revitalization: The moderating role of policy environment. *Int. J. Env. Res. Pub. He* **2023**, *20*, 1768. [CrossRef] [PubMed]
34. Xu, S.T.; Chen, M.L.; Yuan, B.F.; Gu, D.M. The impact of social capital and perceived value on farmers' willingness to participate in rural living environment governance: Based on the SOR model. *Resour. Environ. Yangtze Basin* **2024**, *33*, 448–460. (In Chinese)
35. Qian, M.; Cheng, Z.; Wang, Z.; Qi, D. What affects rural ecological environment governance efficiency? Evidence from China. *Int. J. Env. Res. Pub. He* **2022**, *19*, 5925. [CrossRef] [PubMed]

36. Ye, L.; Wu, Z.H.; Hu, X.M. A review of rural habitat evaluation research in China from a multidisciplinary perspective. *Huazhong Archit.* **2022**, *40*, 141–145. (In Chinese)
37. Simandan, D. The wise stance in human geography. *Trans. Inst. Br. Geogr.* **2011**, *36*, 188–192. [CrossRef]
38. Chen, W.; Zhu, K.; Wu, Q.; Cai, Y.; Lu, Y.; Wei, J. Adaptability evaluation of human settlements in Chengdu based on 3S technology. *Environ. Sci. Pollut. R* **2022**, *29*, 5988–5999. [CrossRef] [PubMed]
39. Li, Y.; Zhang, G.Q.; Yu, G. Index System of Evaluation of Rural Environmental Quality under the Background of Rural Revitalization: A Review. *J. Ecol. Rural. Environ.* **2023**, *39*, 146–155.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

*Article*

# Effects of Urban Greenway Environmental Types and Landscape Characteristics on Physical and Mental Health Restoration

**Saixin Cao [1], Chen Song [1], Siwei Jiang [1], Hao Luo [2], Ping Zhang [1], Yinghui Huang [1], Jian Yu [3], Kai Li [1], Nian Li [1], Baimeng Guo [1] and Xi Li [1,*]**

[1] College of Landscape Architecture, Sichuan Agricultural University, Chengdu 611130, China; caosaixin@gmail.com (S.C.); luckysc188@gmail.com (C.S.); jswjr818@163.com (S.J.); pingzhang@sicau.edu.cn (P.Z.); mryinghui@gmail.com (Y.H.); 14908@sicau.edu.cn (K.L.); nli@sicau.edu.cn (N.L.); 71393@sicau.edu.cn (B.G.)
[2] Guangdong Provincial Key Laboratory of Silviculture Protection and Utilization, Guangdong Academy of Forestry, Guangzhou 510520, China; laluohao@sinogaf.cn
[3] School of Architecture and Civil Engineering, Xihua University, Chengdu 610039, China; yujian@mail.xhu.edu.cn
* Correspondence: lixi@sicau.edu.cn; Tel.: +028-8629-0876

**Abstract:** As important linear public spaces, urban greenways are highly important for improving public health. Many studies have proven the benefits of urban greenways for human well-being, but fewer studies have focused on the impact of their specific environmental types and characteristics on physical and mental health. In this study, 100 subjects participated in a comparative experiment on three types of urban greenways (urban roads, urban parks, and urban rivers), and corresponding physiological indicator (systolic blood pressure [SBP], diastolic blood pressure [DBP], and pulse) and psychological indicator (perceived restorativeness scale [PRS] and positive and negative affect schedule [PANAS]) data were collected. The results indicated that (1) different greenway environment types lead to different physiological and psychological states; (2) urban park-type greenways (SBP [t = 2.37, $p$ = 0.020], DBP [t = 2.06, $p$ = 0.042], PANAS = 2.80, PRS = 5.39) have the greatest physical and mental recovery benefits, followed by urban river-type greenways (SBP [t = 2.84, $p$ = 0.006], DBP [t = 1.29, $p$ = 0.200], PANAS = 2.30, PRS= 5.02) and urban road-type greenways (SBP [t = 0.78, $p$ = 0.440], DBP [t = 0.37, $p$ = 0.716], PANAS = 2.00, PRS = 4.15); (3) plant color and layer diversity have a significant positive impact on the mental health benefits of the three greenway types; (4) the aesthetics of waterscapes and ornaments can significantly improve the perceived restoration ability of urban river-type greenways; and (5) the comfort of pathways and facilities can effectively promote the psychological recovery potential of urban road-type greenways. These findings systematically demonstrate for the first time the differences in restoration potential among urban greenways of different environmental types and summarize the key landscape characteristic predictors influencing the restoration potential of various types of urban greenways. Our research provides new ideas for proactive greenway interventions for physical and mental health and for enriching the restorative environmental science system.

**Keywords:** urban greenway; restorative environment; environmental types; landscape characteristics; urban green spaces; public health

**Citation:** Cao, S.; Song, C.; Jiang, S.; Luo, H.; Zhang, P.; Huang, Y.; Yu, J.; Li, K.; Li, N.; Guo, B.; et al. Effects of Urban Greenway Environmental Types and Landscape Characteristics on Physical and Mental Health Restoration. *Forests* **2024**, *15*, 679. https://doi.org/10.3390/f15040679

Academic Editor: Fausto Manes

Received: 2 March 2024
Revised: 4 April 2024
Accepted: 8 April 2024
Published: 9 April 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Rapid urbanization has led to an increasing proportion of the global population residing in urban areas. As of 2021, the urban population worldwide constituted 56% of the total population, a figure projected to increase to 68% by 2050 [1]. High-density urban living environments and fast-paced urban lifestyles have resulted in widespread mental

fatigue and psychological issues among residents, posing significant health challenges worldwide [2]. As an important place for residents to get close to and feel nature, urban green spaces (UGSs) have been shown to be an important means of addressing adverse health conditions [3,4]. These environments have demonstrated positive effects on fostering positive emotions [5], alleviating anxiety and stress [6], enhancing cognitive abilities [7], and reducing the incidence and mortality rates of cardiovascular and respiratory diseases [8,9].

Urban greenways connect urban natural habitats and communities because of their linear characteristics. While protecting biodiversity, they help crowded cities improve opportunities for positive interactions between people and nature, becoming an important part of UGSs. Serving as nearby natural settings for urban residents, urban greenways offer the surrounding population opportunities for commuting and physical activities [10], spaces for relaxation and leisure [11], and spaces that foster physical and mental health restoration [12]. In addition to providing a physical environment that supports outdoor activities, urban greenways also provide social capital and enhance social cohesion, which together benefit residents' physical and mental health [13]. Therefore, urban greenways might possess different capabilities than those offered by other UGSs, enabling them to integrate natural resources while promoting the restoration of public health. Researching the restorativeness of urban greenways could help provide nature-based solutions for high-quality urbanization [14].

Currently, two mainstream theories suggest that exposure to nature has restorative effects on human health: attention recovery theory (ART) and stress reduction theory (SRT). ART, proposed by Kaplan [15], suggests that the restorativeness of the natural environment is mainly reflected in the restoration of attention. Nondirected attention activities (observing nature) that do not require energy consumption will have a recovery effect on directed attention (work and study). SRT, introduced by Ulrich [16], suggests that natural environments can relieve stress and help calm excitement, thereby allowing rapid recovery from short-term stress. The two theories basically matured in the early 1990s. Because they were produced at the same time, they also supplemented and improved their respective views during mutual debates. In line with the restorativeness theory, Hartig defines restorative environments as spaces where individuals can disengage and relax, fostering positive recovery effects, and that provide a means of escape from everyday life [17]. Based on restorative theory, many scholars have explored the relationship between UGSs and public health. Research has revealed that the environmental types [18], environmental elements [19], and spatial characteristics [20] of UGSs are significant factors influencing the restoration of physical and mental health. Natural environments better enable health recovery than urban environments; however, not all natural environments exhibit the same level of restorativeness [21], and there are differences in the restorative properties of the various elements of natural environments. Topographic landscapes with natural mountain forests have a strong restorative effect [18]. Enhancing the quality of elements such as trees, lawns, flowers, and water bodies is a reliable method for increasing the restoration benefits of UGSs [22,23]. In conclusion, UGSs exhibit diverse restorative benefits, and different types of green environments possess varying restoration potentials due to differences in environmental characteristics. Landscapes with various natural elements may offer better restoration because they are more likely to meet different needs and provide resources for various restorative experiences.

As a special type of UGSs, urban greenways stimulate more physical activity and are better at predicting health than traditional urban parks due to their linear characteristics [24]. Natural elements, recreational facilities, road quality, and cleanliness have been proven to be important factors affecting the use and well-being of urban greenways [13,25,26]. The attributes of greenways may affect the use of greenways through place attachment [26], place preference [27], environmental perception [28], cultural value [29], the promotion of sports activities [30], and social interaction [31], thereby improving the health and well-being of residents. In summary, there is a close connection between the environmental quality of urban greenways and health and well-being. However, as an emerging green

space type, research on urban greenways and public health has focused only on the use and overall impact of greenways. In this research, two comparative studies on large-scale, multifunctional urban greenway interventions attracted our interest: Hunter et al. [32] evaluated the physical activity, quality of life, and mental health of residents before and after the Connswater Community Greenway (CCG) intervention in Northern Ireland in approximately 2010 and 2017. This study was one of the first to assess the multifunctionality of urban greenway interventions. The results indicated that, at the current stage, the CCG did not significantly improve physical activity behavior or mental health in the population. Xie et al. [30] studied the impact of large-scale urban greenway interventions on public health for the first time in China. Two rounds of survey data (before and after the intervention in 2016 and 2019, respectively) showed that the Wuhan East Lake Greenway intervention significantly improved residents' physical activity and physical health. The two seemingly contradictory conclusions from two similar studies conducted during the same period prompted us to conduct a further comparison. The CCG is an urban greenway constructed along three rivers, while the Donghu Greenway mainly relies on urban parks and lakes. Numerous studies have demonstrated that the environmental type and elements of UGSs are crucial factors influencing health recovery. Therefore, we propose the following hypothesis: Differences in the environmental types of urban greenways affect health recovery potential. This suggests that the impact of urban greenways on public health may require more nuanced and specific assessments rather than investigating their effects on health at an abstract, general level.

The focus of urban greenways is to connect and enhance existing green spaces, and their typological differences are largely influenced by the land use types in the surrounding areas. In previous studies, urban greenways were categorized into three types based on the resources they used: (1) urban road-type greenways established along city roads, (2) urban park-type greenways integrated within city parks, and (3) urban river-type greenways developed along urban river systems [33,34]. Although this classification distinguishes differences in the types and characteristics of urban greenways, no research has yet conducted a more in-depth investigation into whether these differences affect the realization of benefits related to urban greenways (such as health restoration benefits). Therefore, this study investigates these three types of urban greenways to record the physical and mental recovery experiences of the population to explore the following two scientific questions: (1) Are there variations in physical and mental health recovery capabilities across environmental types of urban greenways? and (2) Which landscape characteristics in various types of urban greenways influence the restorative effects? Through this research, we aim to provide a theoretical foundation for more rational planning and configuration of environmental types and characteristics of urban greenways. This endeavor will enable more targeted construction of restorative environments along greenways, enhancing the quality of residents' restorative experiences and providing evidence-based practices towards achieving human-centered habitat construction goals.

## 2. Materials and Methods

### *2.1. Participants*

This study included a total of 100 participants, with ages ranging from 18 to 30 years (mean age = 23.15 years, SD = 2.32, maximum age = 30 years, minimum age = 18 years). According to the central limit theorem, when the sample size exceeds 30, the sampling distribution of the mean tends to approach a normal distribution. Hence, a sample size of 100 individuals met the requirements for subsequent statistical analyses. The gender distribution among the 100 participants was equal, with 50 males and 50 females, with the aim of minimizing interference and bias resulting from gender imbalance. To expand the sample size and enhance representativeness, we recruited volunteers by posting posters on university campuses and in communities around the greenways in the Chengdu urban area and utilized online social platforms (WeChat group chats) to disseminate advertisements. All volunteers were healthy residents with Chinese as their native language. They entered

the online registration system (WPS online form) to register voluntarily by scanning the QR code on online and offline posters. Once the number of male and female participants reached 50 each, the registration system automatically closed. Apart from controlling for sex, no other specific criteria were applied during the participant selection process to avoid potential biases. All participants were informed of the experimental procedures and associated risks and signed an informed consent form before the trial. Participants were instructed to refrain from smoking, drinking alcohol, and engaging in strenuous physical activities throughout the entire study period. Although we had to exclude a small number of participants from the data analysis due to incomplete data or technical issues, we believe that the overall sample size ($n$ = 93, men = 47) is still sufficient to support this study. The study was conducted in accordance with the Declaration of Helsinki. The study was conducted with the approval of the Academic Ethics Committee of the College of Landscape Architecture, Sichuan Agricultural University, China (project identification code: 20220017).

### 2.2. Study Sites and Materials

As visual replicas of real landscapes, images are widely used in research because this method is time-saving and cost-effective while allowing better control of external interfering variables during experiments. Therefore, as the stimulus source material of this study, the shooting and selection of greenway photos were particularly important.

Chengdu has the world's largest greenway system, the Tianfu Greenway. The total length of the Tianfu Greenway is 16,900 km, with excellent ecological background and wide coverage of landscape features, enabling it to effectively represent the development status of China's greenways. We first conducted an on-site investigation of three types of urban greenways in Chengdu city. The following criteria had to be met when selecting greenway sections: (1) the entire section is located within the urban area of Chengdu and meets the requirements of urban greenways; (2) the sections are located in different areas of Chengdu to ensure the representativeness and universality of the sample; (3) the landscape features are obvious and can better reflect the characteristics of various urban greenways; and (4) the flow of people is large and the frequency of use is high. Finally, a total of six sections of three types of urban greenways were selected (Figure 1). These surveys covered seven urban districts, Jinjiang, Qingyang, Jinniu, Wuhou, Chenghua, Wenjiang, and Shuangliu, for a total surveyed greenway distance of 23 km. Specifically, the Jinjiang Greenway (Huoshui Park to Hejiang Pavilion section) in Jinjiang District, the Panda Greenway (Jiaozi Interchange to Chengyu Interchange section) spanning Jinjiang and Chenghua Districts, the Jincheng Greenway (Jincheng Lake to Guixi Ecological Park section) in Wuhou District, the Panda Greenway (Supo Interchange to Yangxi Interchange section) crossing Qingyang and Jinniu Districts, the Jincheng Greenway (Intangible Heritage Park to Shuxian Scenic Area section) spanning Qingyang and Shuangliu Districts, and the Nancheng Greenway (Binjiang Bridge to Biluo Lake Park section) located in Wenjiang District were included.

After the investigation, we opted to capture real scenes of the greenways in autumn (15 November–30 November 2022), when the landscape undergoes obvious seasonal changes and is highly ornamental. The photography of the greenways followed specific standards: (1) photographs were taken under good weather conditions, either clear or partly cloudy skies, between 9 a.m. and 4 p.m.; (2) a Sony A7M2 camera equipped with a Sony 28–70 mm full-frame standard zoom lens (FE 28–70 mm f/3.5–5.6) was used; (3) a tripod was utilized to position the camera at a height of 1.5 m, maintaining a horizontal field of view while minimizing nonlandscape elements within the frame; and (4) images were captured at observation points along the main scenic pathways, with shots taken every 20 m. A total of 1132 landscape photographs of the six sampled greenway segments were taken in compliance with these criteria.

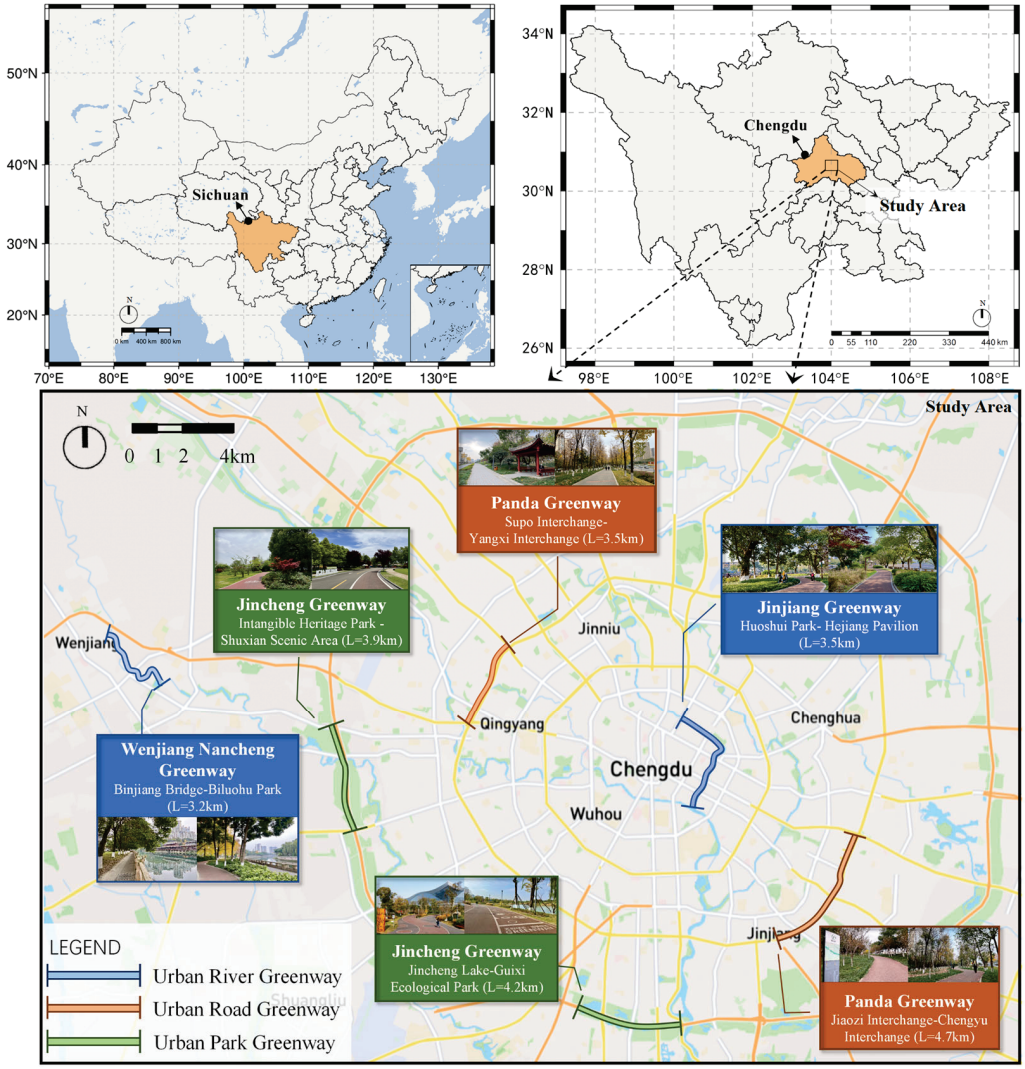



**Figure 1.** Location of the research site.

After the images were taken, we further refined the images to ensure that the results were robust. The specific criteria for evaluation were as follows: (1) photos with dim lighting or blur were excluded; (2) photos with unnatural compositions that made it difficult to focus on the greenway environment were excluded; (3) photos with similar environmental characteristics were decreased to selected photos that reflected the specificity of the landscape features; and (4) photos with poor landscape effects, such as obvious garbage, serious damage to facilities, and poor vegetation, were excluded. Finally, 10 landscape architecture experts selected a total of 60 photos that could fully and truly reflect the environmental characteristics of the three types of urban greenways (20 photos for each of the three types of greenways) as stimulus materials for subsequent experiments. For details, see the Supplementary Materials (Figure S1).

### *2.3. Procedure*

Before the experiment, the 100 participants were asked to avoid smoking, drinking, and undertaking strenuous physical activity. In this study, the experiments were conducted simultaneously in two laboratories. Each experiment lasted 45 min. Two subjects in each laboratory participated in the experiment at the same time. Each laboratory could handle 25 subjects per day, and the experiment was completed in two days.

Each subject experienced three types of greenway stimulation through five steps: experimental preparation, stress tests, pretests, greenway stimulation, and post-tests (Figure 2).

Before entering the laboratory, participants first completed a demographic characteristics scale to report their basic information and signed an informed consent form. After entering the laboratory, the experimenter put the experimental equipment on the participants and explained the experimental procedures. According to previous studies, 1–5 min of rest can make people relaxed and calm [35,36]; therefore, after putting on the instrument, the subjects closed their eyes for 1.5 min to reach a calm and relaxed state before starting the experiment. Participants were initially exposed to a 1.5 min stress video (traffic noise video, construction noise video, or noisy rock live video) to simulate daily high-pressure and mentally tense situations. Previous research has effectively used similar scenarios to induce physical and mental stress [37–39]. The experimenter closely monitored the participants' emotional states throughout the entire process and ensured that they had the right to withdraw from the stress video at any time. During the two-day experiment, two participants questioned slightly elevated sound levels, and the experimenter promptly addressed their concerns. Subsequently, pretest data for physiological and psychological measures (blood pressure, pulse, and positive and negative affect schedule [PANAS]) were collected. Ulrich's research has shown that immersion in a natural environment for 3–5 min yields significant physical and mental restoration effects [40]. Hence, after the pretest, participants viewed photos of the first greenway for 5 min (comprising 20 images, each displayed for 15 s). Following this, they completed various questionnaires (Perceived Restorativeness Scale [PRS], PANAS, and Environmental Characteristics Perception Scale) and underwent physiological data measurements, totaling 5 min for the post-test. When completing the questionnaire, a combination of photos of the current greenway landscape (involving all landscape features; see Supplementary Materials Figure S1 for details) was provided to help the participants perceive the overall environment of this type of greenway. After the post-test, the first section of the greenway experiment ended, totaling 15 min.

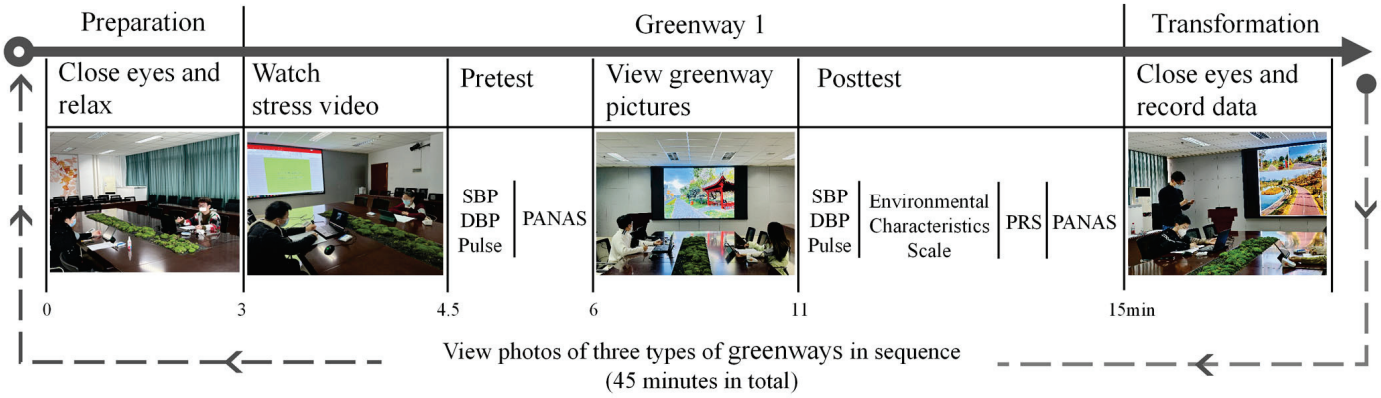



**Figure 2.** Experiment flow chart. SBP: systolic blood pressure; DBP: diastolic blood pressure; PANAS: positive and negative affect schedule; PRS: perceived restorativeness scale.

After viewing a greenway, the subjects sat quietly with their eyes closed for 1.5 min before viewing another type of greenway to eliminate the legacy effect. After the three greenway tests were completed, the subjects received their remuneration, and the experiment ended. The total experimental time for each participant was approximately 45 min. Notably, the experimenters simultaneously adjusted the viewing sequence of the greenways within each experimental group to eliminate order effects. For instance, there were six possible playback sequences, such as 1-2-3 (Group 1), 1-3-2 (Group 2), and 2-3-1 (Group 3). The total number of groups for morning or afternoon sessions was also six, completing a full cycle.

### *2.4. Measurements*

#### 2.4.1. Environmental Characteristics Measurement

The Greenway Environmental Characteristics Perception Scale reflects the overall environmental characteristics of urban greenways. The "Sichuan Province Urban and

Rural Greenway Planning and Design Standards (DBJ51/T097-2018)" divides greenway environmental elements into four categories: greenway trails, greenway vegetation, rest stations, and facility systems [41]. Liao divided the components of urban greenways into paths, plants, water systems, facilities, and signs [34]. Chang et al. roughly divided the construction characteristics of urban greenways into five categories: trails, nature, water bodies, facilities, and surrounding landscapes, and each characteristic is evaluated through the two dimensions of component type and construction quality [13,25].

Based on previous relevant research and combined with field surveys of urban greenways, we noticed that among the many environmental elements of greenways, pathways, vegetation, facilities, water bodies, and ornaments are most often mentioned and appear most frequently. Therefore, we initially divided greenway environmental characteristics into the above five environmental dimensions. Each dimension is evaluated mainly based on measurement indicators such as aesthetics, comfort, and richness. From the perspective of intuitive visual perception, aesthetics and richness are easier-to-perceive features of the landscape environment, while from the perspective of recreational experience, comfort is a more important influencing factor. In the end, there were approximately 3 items under each environmental dimension, using a 5-point Likert scale. The entire Greenway Environmental Characteristics Perception Scale measured a total of 5 environmental dimensions and 18 environmental characteristics. The scale subsequently passed reliability (Cronbach's alpha = 0.921) and validity (KMO = 0.907, Bartlett's test $p < 0.05$) tests. Each respondent completed the greenway characteristics scale after viewing each greenway landscape. The complete scale is shown in the Supplementary Materials (Table S1).

#### 2.4.2. Physiological Measures

This experiment utilized a portable electronic blood pressure monitor (YUWELL, YE660C, Danyang, Jiangsu, China) placed on each participant's left arm to measure systolic pressure (mmHg), diastolic pressure (mmHg), and pulse rate (bpm). Each participant had their physiological data measured twice—once after the stress test and again after observing the greenway pictures. Blood pressure and pulse rate reflect the state of physiological arousal or relaxation in the human body [42,43].

#### 2.4.3. Psychological Measures

According to ART and SRT, the relationship between UGSs and mental health is mainly based on perceptual recovery and emotional recovery. This study used the Perceived Restorativeness Scale (PRS) to measure the perceived restorativeness of greenways. This scale was developed by Hartig based on the ART proposed by Kaplan and evaluates the perceived restorative quality of an environment in terms of being away, fascination, compatibility, and extent [44,45]. To avoid respondent fatigue, this study adopted Huang et al.'s revised short version of the scale, which consists of a total of 18 items and passes reliability, validity, and confirmatory factor analysis tests [46]. Each respondent completed the PRS after viewing a section of the greenway landscape. The complete scale is shown in the Supplementary Materials (Table S2).

This study employed the Positive and Negative Affect Schedule (PANAS) to measure emotional recovery. The PANAS, developed by Watson et al. in 1988, is a well-established and widely recognized scale for assessing emotions. It consists of 20 items (10 for positive affect [PA] and 10 for negative affect [NA], arranged in random order) to gauge both positive and negative emotions [47,48]. Each participant completed the PANAS questionnaire twice—once after the stress test and again after viewing the greenway landscapes. The complete scale can be found in the Supplementary Materials (Table S3).

### *2.5. Statistical Analysis*

This study utilized SPSS 26.0 (IBM Corp. Armonk, NY, USA) to first describe the participants' demographic characteristics and analyze their impact on physical and mental recovery. Subsequently, the data were tested for reliability and validity. Once validated,

paired *t*-tests, one-way ANOVA, Wilcoxon signed-rank tests, and Kruskal-Wallis tests were employed to examine the influence of the type of urban greenway environment on physiological and psychological restoration benefits. Next, stepwise regression analysis was conducted to explore the relationships between various landscape characteristics of urban greenways and mental recovery.

## 3. Results

### *3.1. Urban Greenways and Physiological Recovery*

The results of paired *t*-tests analyzing systolic and diastolic blood pressure as well as pulse data before and after viewing are presented in Figure 3. After observing the urban park-type greenways, participants exhibited significant decreases in systolic pressure (104.8 ± 14.7 and 103.0 ± 13.42, t = 2.367, $p = 0.020$) and diastolic pressure (68.2 ± 11.1 and 66.8 ± 12.0, t = 2.061, $p = 0.042$), while pulse did not significantly change (77.6 ± 10.2 and 77.4 ± 10.7, t = 0.216, $p = 0.829$). After observing urban river-type greenways, participants showed highly significant decreases in systolic pressure (104.5 ± 14.1 and 102.4 ± 14.6, t = 2.838, $p = 0.006$), whereas diastolic pressure (67.83 ± 11.8 and 67.10 ± 11.1, t = 1.290, $p = 0.200$) and pulse (77.16 ± 10.9 and 76.33 ± 10.3, t = 1.370, $p = 0.174$) exhibited no significant changes. Following the observation of urban road-type greenways, participants showed no significant changes in their physiological parameters (systolic pressure [103.9 ± 13.0 and 103.2 ± 12.5, t = 0.776, $p = 0.440$], diastolic pressure [67.5 ± 11.1 and 67.3 ± 12.3, t = 0.366, $p = 0.716$], or pulse [77.6 ± 10.6 and 77.2 ± 10.8, t = 0.583, $p = 0.561$]).

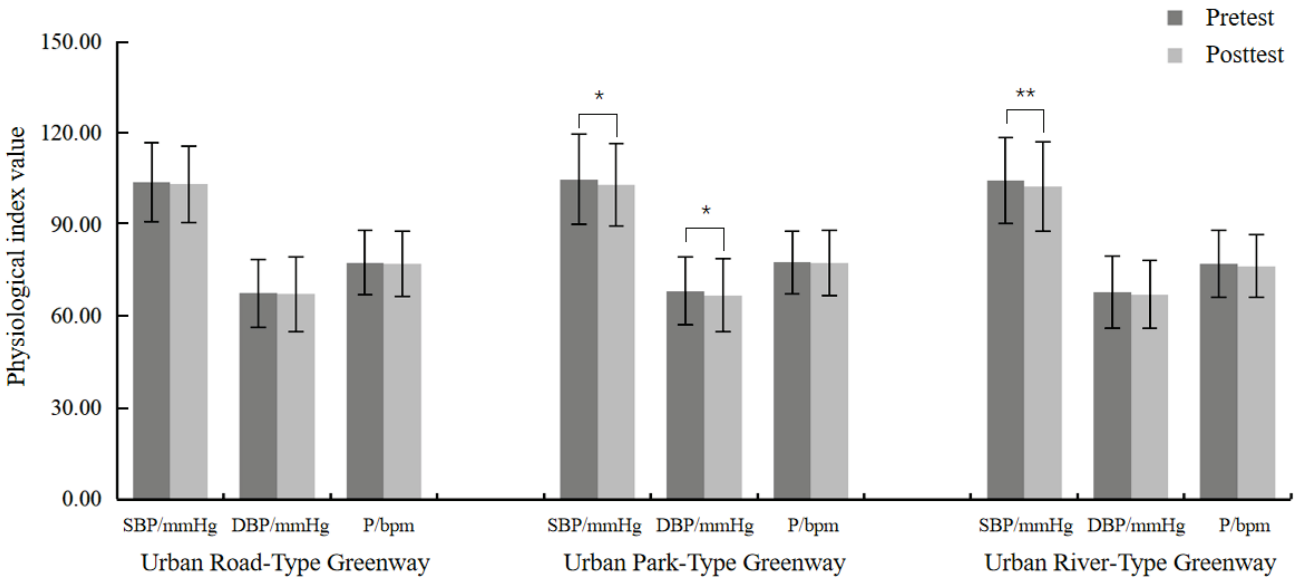



**Figure 3.** Blood pressure and pulse changes before and after participants viewed the three types of greenways. $n = 93$; means ± SDs; * $p < 0.05$, ** $p < 0.01$; validated by paired *t*-tests.

### *3.2. Urban Greenways and Psychological Restoration*

#### 3.2.1. Emotional Recovery

As shown in Figure 4, after observing the three urban greenway types, participants demonstrated significant increases in PA scores and significant decreases in NA scores, albeit with varying degrees of change. Wilcoxon signed-rank tests revealed that after observing urban road-type greenways, participants exhibited significant increases in PA (1.80 and 2.60, Z = 7.424, $p < 0.01$) and significant decreases in NA (2.80 and 1.10, Z = −8.296, $p < 0.01$). Following the observation of urban park-type greenways, participants showed significant increases in PA (1.80 and 3.20, Z = 8.088, $p < 0.01$) and significant decreases in NA (2.80 and 1.10, Z = −8.377, $p < 0.01$). Similarly, after observing urban river-type greenways, participants displayed significant increases in PA (1.80 and 3.00, Z = 8.009, $p < 0.01$) and significant decreases in NA (2.50 and 1.10, Z = −8.187, $p < 0.01$). The results also indicated

that after observing the three types of greenways, the urban park-type greenways yielded the highest PA scores and the lowest NA scores.

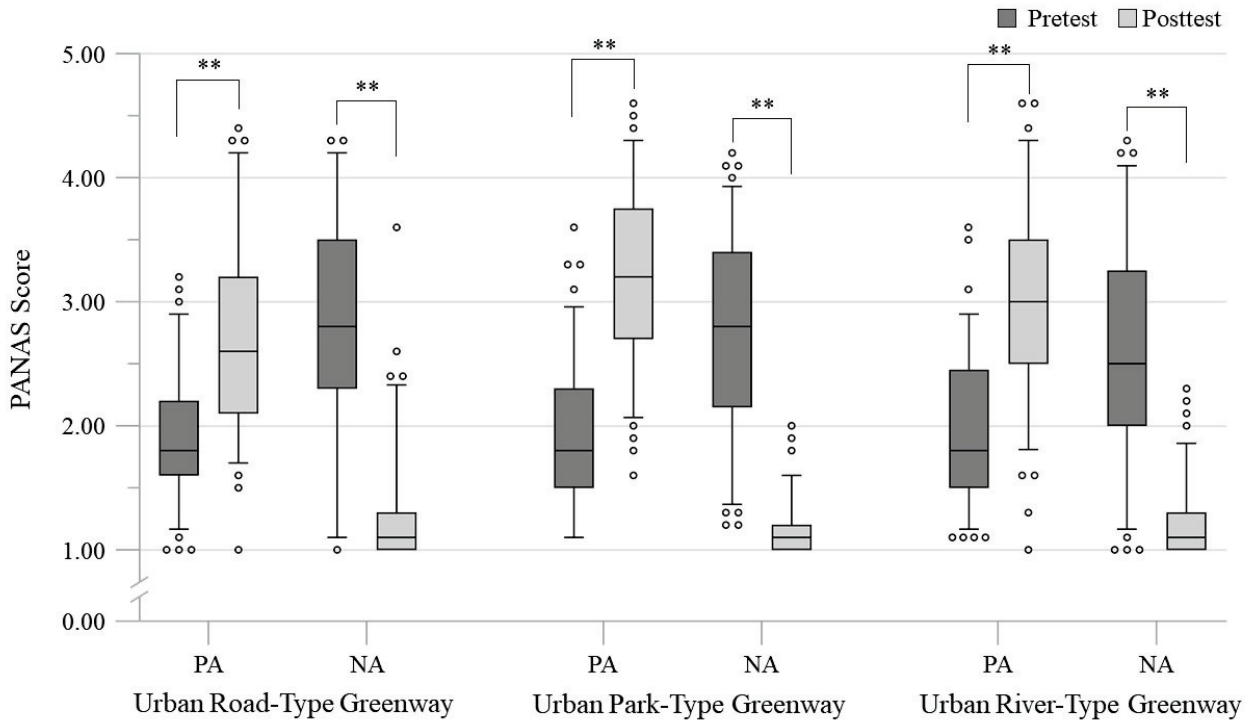



**Figure 4.** Changes in the PANAS scores before and after participants viewed the three greenway types. PA: positive affect; NA: negative affect. $n = 93$; the data shown are medians (central lines), interquartile ranges (box margins), adjacent values (whiskers), and outliers (dots); ** $p < 0.01$; validated by paired Wilcoxon tests.

After further comparing the increases in PA, decreases in NA, and total emotional changes (the sum of the former two), for the three types of greenways (Figure 5), the Kruskal-Wallis test revealed significant intergroup differences in the increases in PA (H = 22.832, d.f. = 2, $p < 0.01$) and total emotional changes (H = 10.041, d.f. = 2, $p < 0.01$) among participants after visiting different greenways. However, there was no significant intergroup difference in the decrease in NA (H = 2.972, d.f. = 2, $p = 0.226$). Bonferroni post hoc correction was used for pairwise comparisons among groups that showed significant intergroup differences. The increases in PA in urban park-type greenways were significantly greater than those in urban road-type (1.30 and 0.60, adjusted $p < 0.01$) and urban river-type greenways (1.30 and 1.00, adjusted $p < 0.05$). Additionally, the increases in PA in urban river-type greenways were significantly greater than those in urban road-type greenways (1.00 and 0.60, adjusted $p < 0.05$). In terms of total emotional change, the urban park-type greenways exhibited significantly greater changes than did the urban road-type (2.80 and 2.00, adjusted $p < 0.01$) and urban river-type greenways (median: 2.80 and 2.30, $p < 0.05$).

A stepwise linear regression analysis was performed on the emotional recovery ability of urban greenways and various environmental characteristics (Table 1). The results showed that the environmental characteristics of the three types of urban greenways explained 32.8%, 21.9%, and 8.8% of the emotional recovery benefits. For urban road-type greenways, suitable pathway width ($\beta = 0.273$, t = 3.025, $p = 0.003$), an abundance of landscape ornaments ($\beta = 0.234$, t = 2.361, $p = 0.020$), and well-maintained pathway paving ($\beta = 0.211$, t = 2.194, $p = 0.031$) emerged as crucial environmental factors enhancing emotional recovery capacity. Interestingly, a negative correlation was found between good water affinity ($\beta = -0.531$, t = −3.456, $p = 0.001$) and the emotional recovery potential of urban road-type greenways. Within urban park-type greenways, rich plant colors ($\beta = 0.253$, t = 2.540, $p = 0.013$), good vegetation shading effects ($\beta = 0.246$, t = 2.641, $p = 0.010$), and suitable

pathway widths (β = 0.228, t = 2.269, $p$ = 0.026) were identified as key environmental features that enhance emotional recovery capacity. Rich plant layers (β = 0.313, t = 3.141, $p$ = 0.002) emerged as a key feature in boosting the emotional recovery capacity of urban river-type greenways.

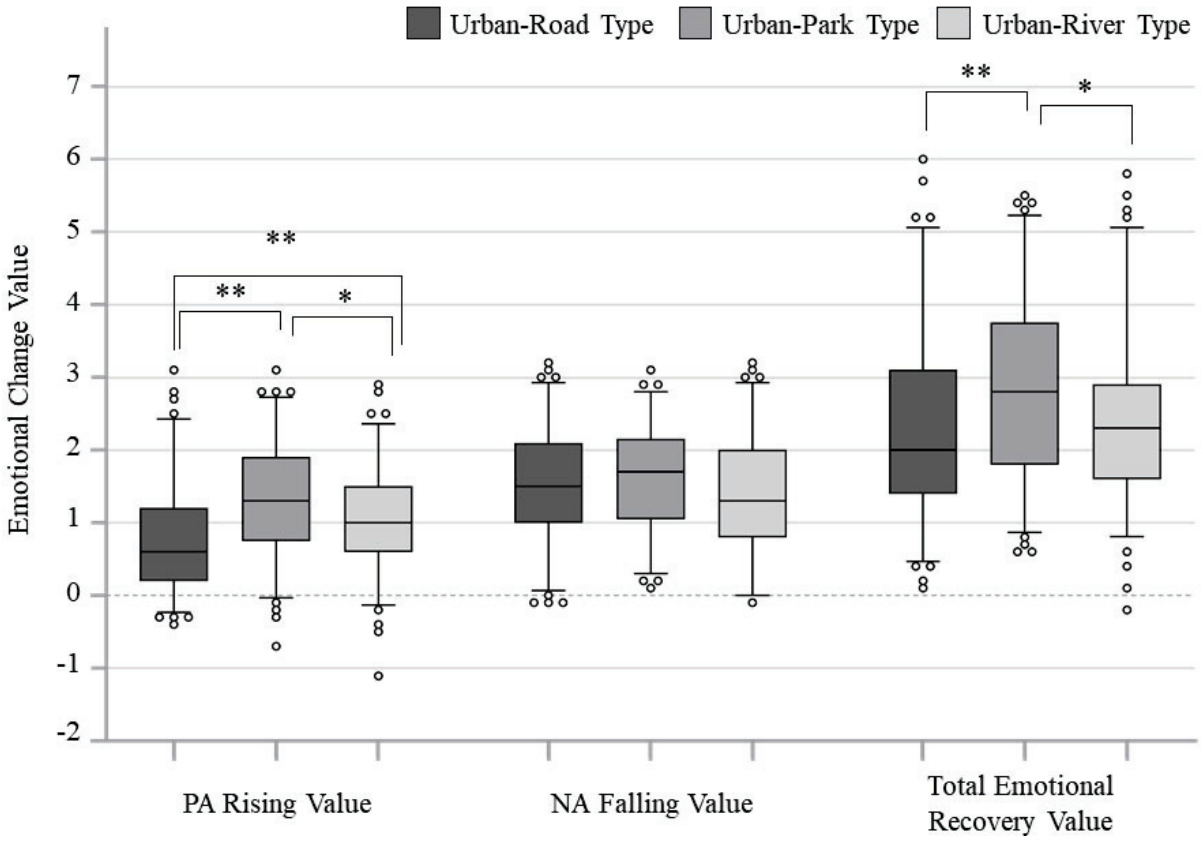



**Figure 5.** Differences in PA, NA, and total emotional recovery values among the three greenway types. $n$ = 93; the data shown are the medians (central lines), interquartile ranges (box margins), adjacent values (whiskers), and outliers (dots); * $p < 0.05$, ** $p < 0.01$; validated by the Kruskal-Wallis test.

**Table 1.** Key landscape characteristics for emotional recovery.

| Dependent and Independent | Standardized Beta | t | $p$ | Collinearity Statistics | |
|---|---|---|---|---|---|
| | | | | Tolerance | VIF |
| **Urban Road Type (Adj. $R^2$ = 0.328; $p < 0.001$)** | | | | | |
| Suitable pathway width | 0.273 | 3.025 | 0.003 | 0.895 | 1.117 |
| Good water affinity | −0.531 | −3.456 | 0.001 | 0.310 | 3.226 |
| Abundance of landscape ornaments | 0.234 | 2.361 | 0.020 | 0.743 | 1.346 |
| Well-maintained pathway paving | 0.211 | 2.194 | 0.031 | 0.788 | 1.269 |
| **Urban Park Type (Adj. $R^2$ = 0.219; $p < 0.001$)** | | | | | |
| Suitable pathway width | 0.228 | 2.269 | 0.026 | 0.840 | 1.190 |
| Good vegetation shading effect | 0.246 | 2.641 | 0.010 | 0.978 | 1.023 |
| Rich plant colors | 0.253 | 2.540 | 0.013 | 0.856 | 1.169 |
| **Urban River Type (Adj. $R^2$ = 0.088; $p < 0.005$)** | | | | | |
| Rich plant layers | 0.313 | 3.141 | 0.002 | 1.000 | 1.000 |

Note: The dependent variable is the mean emotional recovery. Correlations were considered significant at the $p < 0.05$ level.

### 3.2.2. Perceived Restoration

Table 2 shows the differences in scores among the three types of greenways across PRS dimensions. The PRS total score was analyzed using one-way ANOVA, while the

other four dimensions were assessed using the Kruskal-Wallis rank-sum test. The results indicate significant intergroup differences between the three greenway types across all PRS dimensions: being away [d.f. = 2, H = 47.908, $p < 0.01$]; extent [d.f. = 2, H = 41.489, $p < 0.01$]; fascination [d.f. = 2, H = 59.207, $p < 0.01$]; compatibility [d.f. = 2, H = 50.938, $p < 0.01$]; and PRS total score [d.f. = 2, F = 36.69, $p < 0.01$]. Except for the being away dimension, urban park-type greenways scored significantly higher than did urban road-type and urban river-type greenways across all PRS dimensions. Urban river-type greenways also scored significantly higher than did urban road-type greenways across all PRS dimensions. There was no significant difference in the scores of urban park-type greenways and urban river-type greenways in the being away category, but they were both higher than the scores of urban road-type greenways.

**Table 2.** Differences in PRS scores among the three greenway types ($n$ = 93).

| | Being Away | Extent | Fascination | Compatibility | Overall Restoration |
|---|---|---|---|---|---|
| Urban road type | 4.00 $^{b}$ | 4.00 $^{c}$ | 4.25 $^{c}$ | 4.20 $^{c}$ | 4.15 $^{c}$ |
| Urban park type | 5.60 $^{a}$ | 5.50 $^{a}$ | 5.50 $^{a}$ | 5.60 $^{a}$ | 5.39 $^{a}$ |
| Urban river type | 5.00 $^{a}$ | 5.00 $^{b}$ | 5.25 $^{b}$ | 5.00 $^{b}$ | 5.02 $^{b}$ |

Note: Verified by the Kruskal-Wallis test and one-way ANOVA. Different lowercase letters indicate that the PRS scores are significantly different among the different greenway types at $p < 0.05$ according to the Bonferroni correction.

A comparison of the scores across various PRS dimensions for the three types of greenways is presented in Table 3. For urban roadway greenways, there were higher scores for extent and compatibility, while being away and fascination scored lower. For urban park-type greenways, there were higher scores for fascination and compatibility and slightly lower scores for being away and extent. For urban river-type greenways, the scores were greater for fascination and extent but lower for compatibility and being away.

**Table 3.** PRS score differences for each greenway type ($n$ = 93).

| | Urban Road Type | | Urban Park Type | | Urban River Type | |
|---|---|---|---|---|---|---|
| | Mean Rank | Ranking | Mean Rank | Ranking | Mean rank | Ranking |
| Being away | 182.69 | 3 | 183.20 | 3 | 179.00 | 4 |
| Extent | 194.30 | 1 | 179.80 | 4 | 188.10 | 2 |
| Fascination | 178.61 | 4 | 195.44 | 1 | 195.28 | 1 |
| Compatibility | 190.40 | 2 | 187.56 | 2 | 183.62 | 3 |

Note: Verified by the Kruskal-Wallis test. A rank was awarded to each PRS dimension based on the mean rank.

Stepwise linear regression analysis of the perceived restoration ability and environmental elements of urban greenways (Table 4) revealed that the environmental characteristics explained 64.2%, 46.2%, and 49.0% of the perceived restoration benefits for the three types of urban greenways, respectively. Rich plant layers ($\beta = 0.287$, t = 3.620, $p < 0.001$) and well-maintained service facilities ($\beta = 0.236$, t = 3.309, $p = 0.001$) emerged as key environmental factors for enhancing the perceived restoration ability of urban road-type greenways. Rich plant layers ($\beta = 0.441$, t = 5.295, $p < 0.001$), good water affinity ($\beta = 0.242$, t = 2.881, $p = 0.005$), and suitable pathway slopes ($\beta = 0.238$, t = 2.907, $p = 0.005$) were pivotal environmental features for enhancing the perceived restoration ability of urban park-type greenways. For urban river-type greenways, rich plant layers ($\beta = 0.254$, t = 2.626, $p = 0.010$), high aesthetic quality of the water body ($\beta = 0.387$, t = 4.725, $p < 0.001$), and high aesthetic value of landscape ornaments ($\beta = 0.241$, t = 2.874, $p = 0.005$) were key environmental elements for increasing restoration ability.

**Table 4.** Key landscape characteristics affecting perceived restoration.

| Dependent and Independent | Standardized Beta | t | $p$ | Collinearity Statistics | |
|---|---|---|---|---|---|
| | | | | Tolerance | VIF |
| **Urban Road Type (Adj. $R^2$ = 0.642; $p$ < 0.001)** | | | | | |
| Rich plant layers | 0.287 | 3.620 | 0.000 | 0.619 | 1.617 |
| Well-maintained service facilities | 0.236 | 3.309 | 0.001 | 0.765 | 1.307 |
| Good vegetation shading effect | 0.163 | 2.337 | 0.022 | 0.805 | 1.243 |
| High pathway comfort | 0.160 | 2.055 | 0.043 | 0.642 | 1.557 |
| **Urban Park Type (Adj. $R^2$ = 0.462; $p$ < 0.001)** | | | | | |
| Rich plant layers | 0.441 | 5.295 | 0.000 | 0.841 | 1.190 |
| Suitable pathway slope | 0.238 | 2.907 | 0.005 | 0.874 | 1.144 |
| Good water affinity | 0.242 | 2.881 | 0.005 | 0.827 | 1.209 |
| **Urban River Type (Adj. $R^2$ = 0.490; $p$ < 0.001)** | | | | | |
| Rich plant layers | 0.254 | 2.626 | 0.010 | 0.591 | 1.691 |
| High aesthetic quality of the water body | 0.387 | 4.725 | 0.000 | 0.827 | 1.210 |
| High aesthetic value of landscape ornaments | 0.241 | 2.874 | 0.005 | 0.785 | 1.273 |
| Rich plant colors | 0.211 | 2.320 | 0.023 | 0.668 | 1.496 |
| Adequate service facilities | −0.186 | −2.264 | 0.026 | 0.823 | 1.214 |

Note: The dependent variable is the perceived restoration mean. Correlations were considered significant at the $p < 0.05$ level.

## 4. Discussion

### *4.1. Greenway Environment Types and Psychophysiological Recovery*

This study explored the psychophysiological recovery effects of individuals exposed to various types of greenway environments. The results indicate that participants experienced varying degrees of psychophysiological restoration after observing the three types of greenways. However, significant differences were observed between the levels of physical relaxation, emotional states, and perceptual recovery abilities associated with these types of greenway environments. This confirms that distinct environmental types have varied effects on the psychophysiological recovery of individuals [22,38], further emphasizing the crucial role of specific environmental characteristics in the restoration experience [18].

Compared to the other two types of greenways, urban park-type greenways demonstrate superior psychophysiological recovery potential. From the perspective of the resources it relies on, urban park-type greenways built on city parks have richer plant communities, which can create a shaded environment and improve the comfort of the microclimate, which is helpful for physiological relaxation [49,50]. Over the last decade, numerous studies have indicated the substantial role of the perceived sensory dimensions (PSDs) of green spaces in facilitating restoration experiences and psychological well-being [51–53]. Most urban park-type greenways have wide lawns on both sides. Natural environments with abundant activity venues and wide views may have extended the space and prospects of urban park-type greenways, increasing the possibility of restoration and generation, and the higher sky openness also improved the physiological and psychological recovery capabilities [54,55]. Therefore, the natural park landscape and open green space environment may jointly improve the fascination and compatibility of urban park-type greenways (Table 3) and promote the healthy restoration benefits of this type of greenway environment. Previous studies have shown that an optimal restorative environment requires a balance of dense vegetation and open views [52,56], and our results support this view. It also aligns with the refuge–prospect theory proposed by Appleton, suggesting that both refuge and prospect landscape qualities are crucial for human survival [57]. The rich trees and shrubs flanking urban park-type greenways might create a refuge for visitors by forming sheltered spaces, while interspersed open grasslands provide a prospect. Such environments with clear views and hiding locations significantly enhance individuals' capacity for health recovery [58].

Urban river-type greenways also possess strong restoration potential. Evidence suggests that exposure to blue spaces can trigger positive physiological and psychological responses [59,60]. Our results further confirm that urban river greenways can not only reduce cortisol levels [24] but also effectively reduce systolic blood pressure. In further detail, urban rivers serve as crucial "air lanes", providing not only cooling but also fresh air to citizens [61–63], collectively increasing physical comfort. On the other hand, certain visual (reflection of light) and auditory (sound of running water) properties of rivers are also potentially attractive and restorative, helping to trigger positive associations and promote psychological recovery [19,64]. From an evolutionary perspective, urban river-type greenways are located at the interface between land and water bodies. Such habitat intersections tend to have stronger biodiversity and are more likely to meet human life needs [65], which has evolutionary significance [19,66,67], and this may cause a positive reaction in the human body. Notably, this experiment occurred in the dry seasons of autumn and winter in Sichuan Province, when the river water level was low and the water body and riverside landscape were boring. Previous studies have shown a strong positive correlation between aesthetic preferences and restoration potential [23,37], and the aesthetic quality of water bodies and riverside plants is an important restoration attribute [68,69]. Therefore, the restorativeness of urban river greenways in this study may have been affected by seasonal deviation.

Urban road-type greenways exhibit weaker environmental restorative characteristics than do other types of greenways. The findings indicate that after experiencing the urban road-type greenways, participants exhibited weaker perceived restoration capabilities in terms of the dimensions of being away and fascination (Table 3). Being away provides a strong contrast between the environment and daily life, as well as an escape from mundane concerns and worries. Fascination occurs when the environment is sufficiently interesting to effortlessly capture people's attention, and both are crucial predictive factors affecting psychological health restoration [70,71]. Hartig suggested that the motivation for visiting green spaces may stem from a desire to escape the stress of urban environments [72]. Research by Macaulay et al. demonstrated that mind wandering in nature may be more effective in improving mood and relieving stress than other forms of experiences, possibly influenced by "a sense of psychological distance from work" [73,74]. These findings align with our observations. Urban road-type greenways are generally constructed between urban roads and buildings along streets. In comparison to the other two types of greenways, these greenways are narrower and more susceptible to external traffic disturbances. After seeing the urban roads and unnatural artificial elements beside such greenways, subjects may associate them with heavier traffic flow and artificial noise and are more likely to think of trivial matters of daily study and work, thereby reducing the remoteness of the environment. A narrower width also makes it more difficult for urban road-type greenways to carry rich landscape structures, thus affecting the generation of fascination and further weakening the recovery benefits of urban road-type greenways. Therefore, when planning urban road-type greenways in the future, it is possible to enhance their restoration benefits by integrating multiple vertical levels of natural vegetation to reduce traffic noise, enhance the sense of "being away", and simultaneously increase their fascination.

### *4.2. Greenway Environment Characteristics and Psychological Restoration*

This study further explored the differences in the restorative capacity of different greenway environmental characteristics. Rich plant colors and layers are identified as crucial environmental features for promoting emotional and perceptual recovery across three types of urban greenways. On the one hand, numerous studies have shown that nature-related environmental features, such as trees, shrubs, and lawns, can enhance subjective well-being (SWB) and positive affect by influencing connectedness to nature (CTN) [75,76], and our study supports these findings. On the other hand, this emphasizes that the complexity and diversity of landscapes not only bring rich perceptual experiences, enhance environmental preferences [77], and provide resources to meet different needs

and behavioral goals [24] but can also increase positive affect by enhancing the perceived wildness of urban greenways [78], thus enhancing recovery benefits. At the same time, compared to other grey infrastructures in cities, the rich strip vegetation in urban greenways significantly enhances ecological connectivity and biodiversity by connecting habitat patches [79–81]. It is more likely to inspire the biophilic characteristics of human beings who love nature and desire to be subordinate to nature [82] and thus promote psychological health recovery [83]. This finding aligns with the biophilia hypothesis, suggesting that humans have an inherent tendency and innate impulse to connect with other forms of life in the evolutionary process [84]. Therefore, landscapes rich in natural elements are often more favored by people. In conclusion, when constructing urban greenways, the rich attributes of their natural elements can be appropriately enhanced to enhance overall psychological restorativeness.

The restorative characteristics of urban river-type and urban road-type greenways, beyond requiring natural richness, differ in emphasis. The former emphasizes aesthetics, while the latter emphasizes comfort. The results show that high-aesthetic-value water bodies and landscape ornaments are crucial environmental characteristics influencing the perceptual restoration of urban river-type greenways. Interestingly, this finding aligns with findings in another similar study on urban river-type greenways: urban river greenways with unclean water bodies and no landscaping may reduce the aesthetic quality of the natural landscape and be detrimental to mental health recovery [28]. We tried to analyze the reasons: why the quality of landscape elements will enhance users' participation in outdoor activities and promote health recovery [13,85]. The water body itself is an important predictor of the restoration of UGSs [86], and as the main support of urban river-type greenways, the aesthetic quality of rivers has a self-evident impact on the overall restoration effect of the greenway environment. In more detail, for water bodies, aesthetic quality (good water quality and a natural visual form) is considered the most crucial restorative attribute [87]. An unsightly river environment can make observers think of unpleasant odors and reduce the attractiveness of water [88]. Poorly maintained landscape structures may be associated with criminal activity because of their cluttered appearance [89], reducing perceived safety. Together, these factors may influence the impact of aesthetic quality on the restorativeness of urban river-type greenways.

In urban road-type greenways, higher road comfort, well-maintained pavements and facilities, and appropriate road width are pivotal factors influencing psychological restoration. Related studies indicate that environmental restorativeness is influenced not only by the environmental quality of green spaces but also by the motivations of residents using these areas [90]. According to the theory of planned behavior (TPB), the main variables that affect behavioral intentions include behavioral attitudes, subjective norms, and perceived behavioral control [91,92]. In other words, the more positive a person's attitude before performing a specific behavior and the stronger the influence he feels from others, the less difficult it is to perform the behavior and the more positive the person's behavioral intention will be. Urban road-type greenways are mostly close to urban arterial roads. Compared with other greenways and sidewalks, they have stronger traffic accessibility and a more comfortable walking environment, making it easier for residents to have behavioral intentions for commuting and exercise [31]. Hence, the functionality and experiential comfort of these greenway environments can significantly impact people's emotions and perceptions. Notably, there is a negative correlation between water body affinity and the emotional restoration capability of urban road-type greenways. Combining surveys and analysis, this could be because water bodies in urban road-type greenway environments are often connected to roadside drains, making them prone to human-induced pollution. This results in poor water quality and aesthetics, discouraging people from approaching these areas and thereby reducing their restorative benefits. Overall, while ensuring the richness of natural elements, the aesthetic attributes and comfort of urban river-type and urban road-type greenways must be selectively enhanced. This will ultimately enhance the overall restorative potential of urban greenway environments.

### 4.3. Limitations and Future Studies

Firstly, the participants in this study were relatively young (mean age = 23.15 ± 2.32 years). Future research should broaden the demographics of participants to include individuals of all age groups and from more diverse social and cultural backgrounds and increase the sample size (to over 300 participants) to enhance the generalizability of conclusions in a more universally objective context. Secondly, the single visual stimulus presented by an image as experimental material may limit the subject's perceptual ability. For example, visual–auditory stimulation has stronger health recovery potential than a single visual stimulus [77]. Therefore, in the future, quantitative research can be conducted in outdoor environments using multisensory and multiple physical and mental measurement methods. This will enable a more comprehensive exploration of the effects of greenway environmental stimuli on health recovery. In addition, further research is needed to determine specific design standards for environmental features that influence recovery (e.g., the optimal visible green index, the width of greenway pathways, and the quantity of facilities). Finally, different seasons will also affect the restorativeness of the environment [93]. This study selected only greenways in autumn in Chengdu as stimulus materials, which may have introduced potential seasonal and regional biases. In the future, longitudinal studies should also be conducted to investigate the effects of regular exposure to various urban greenways across different seasons on both physical and mental health. These issues need to be addressed in a transdisciplinary way also involving psychology or health skills. This will allow for the assessment of the long-term, widespread benefits of greenway exposure on overall well-being.

## 5. Conclusions

Although many studies have proven that urban greenways have a positive impact on human well-being, to our knowledge, this study is the first to systematically compare the health restoration effects of different environmental types and landscape characteristics of urban greenways. Our research results emphasize the importance of guiding urban greenway planning and design based on different environmental types, providing novel references for policymakers and planners. First, different environmental types of urban greenways have different restorative effects, with urban park-type greenways offering the best restoration experience. Second, rich plant colors and layers are important restorative environmental features for every type of urban greenway. At the same time, for urban river-type greenways, waterscapes and ornaments with high aesthetic value are important restoration attributes; for urban road-type greenways, the comfort of facilities and pathways has a significant impact on promoting restoration. These findings suggest that when designing urban greenways, specific environmental elements and characteristics should be selected and configured for different types of urban greenways to maximize the public's restorative experience. This study provides nature-based solutions for achieving high-quality urbanization by exploring the positive impact of urban greenway environments on physical and mental health.

**Supplementary Materials:** The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/f15040679/s1, Figure S1: Three types of urban greenway experiment pictures; Table S1: Greenway Environmental Characteristics Perception Scale; Table S2: Short version of the Revised Perceived Restorativeness Scale (PRS); Table S3: The Positive and Negative Affect Schedule (PANAS).

**Author Contributions:** Conceptualization, S.C.; methodology, S.C.; investigation, S.C., C.S., S.J. and H.L.; formal analysis, S.C.; visualization, S.C.; writing—original draft preparation, S.C.; writing—review and editing, S.C., C.S., S.J., H.L., P.Z., Y.H., J.Y., K.L., N.L., B.G. and X.L.; supervision, X.L.; funding acquisition, X.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China, grant number 31870703.

**Data Availability Statement:** We do not provide public access to the dataset so as to protect the privacy of the participants. Regarding the details of the data, please contact the corresponding author.

**Acknowledgments:** The authors thank the 100 individuals who participated in this study. The authors are also grateful to Yiyue Tang and Dongpu Lin for their contributions to this research during the COVID-19 epidemic.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. UN-Habitat. *World Cities Report*; United Nations Human Settlements Programme: Nairobi, Kenya, 2022.
2. White, M.P.; Elliott, L.R.; Grellier, J.; Economou, T.; Bell, S.; Bratman, G.N.; Cirach, M.; Gascon, M.; Lima, M.L.; Lohmus, M.; et al. Associations between green/blue spaces and mental health across 18 countries. *Sci. Rep.* **2021**, *11*, 8903. [CrossRef] [PubMed]
3. Bratman, G.N.; Anderson, C.B.; Berman, M.G.; Cochran, B.; de Vries, S.; Flanders, J.; Folke, C.; Frumkin, H.; Gross, J.J.; Hartig, T.; et al. Nature and mental health: An ecosystem service perspective. *Sci. Adv.* **2019**, *5*, eaax0903. [CrossRef] [PubMed]
4. Gascon, M.; Zijlema, W.; Vert, C.; White, M.P.; Nieuwenhuijsen, M.J. Outdoor blue spaces, human health and well-being: A systematic review of quantitative studies. *Int. J. Hyg. Environ. Health* **2017**, *220*, 1207–1221. [CrossRef] [PubMed]
5. McMahan, E.A.; Estes, D. The effect of contact with natural environments on positive and negative affect: A meta-analysis. *J. Posit. Psychol.* **2015**, *10*, 507–519. [CrossRef]
6. Hedblom, M.; Gunnarsson, B.; Iravani, B.; Knez, I.; Schaefer, M.; Thorsson, P.; Lundstrom, J.N. Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Sci. Rep.* **2019**, *9*, 10113. [CrossRef] [PubMed]
7. Bratman, G.N.; Hamilton, J.P.; Daily, G.C. The impacts of nature experience on human cognitive function and mental health. *Ann. N. Y. Acad. Sci.* **2012**, *1249*, 118–136. [CrossRef] [PubMed]
8. Maas, J.; Verheij, R.A.; Groenewegen, P.P.; de Vries, S.; Spreeuwenberg, P. Green space, urbanity, and health: How strong is the relation? *J. Epidemiol. Community Health* **2006**, *60*, 587–592. [CrossRef] [PubMed]
9. Tsunetsugu, Y.; Lee, J.; Park, B.-J.; Tyrväinen, L.; Kagawa, T.; Miyazaki, Y. Physiological and psychological effects of viewing urban forest landscapes assessed by multiple measurements. *Landsc. Urban. Plan.* **2013**, *113*, 90–93. [CrossRef]
10. Fitzhugh, E.C.; Bassett, D.R., Jr.; Evans, M.F. Urban trails and physical activity: A natural experiment. *Am. J. Prev. Med.* **2010**, *39*, 259–262. [CrossRef]
11. Hunter, R.F.; Cleland, C.; Cleary, A.; Droomers, M.; Wheeler, B.W.; Sinnett, D.; Nieuwenhuijsen, M.J.; Braubach, M. Environmental, health, wellbeing, social and equity effects of urban green space interventions: A meta-narrative evidence synthesis. *Environ. Int.* **2019**, *130*, 104923. [CrossRef]
12. He, D.; Lu, Y.; Xie, B.; Helbich, M. How greenway exposure reduces body weight: A natural experiment in China. *Landsc. Urban. Plan.* **2022**, *226*, 104502. [CrossRef]
13. Chang, P.-J. Effects of the built and social features of urban greenways on the outdoor activity of older adults. *Landsc. Urban. Plan.* **2020**, *204*, 103929. [CrossRef]
14. Chen, H.; Liu, L.; Wang, L.; Zhang, X.; Du, Y.; Liu, J. Key indicators of high-quality urbanization affecting eco-environmental quality in emerging urban agglomerations: Accounting for the importance variation and spatiotemporal heterogeneity. *J. Clean. Prod.* **2022**, *376*, 134087. [CrossRef]
15. Kaplan, S. The restorative benefits of nature: Toward an integrative framework. *J. Environ. Psychol.* **1995**, *15*, 169–182. [CrossRef]
16. Ulrich, R.S.; Simons, R.F.; Losito, B.D.; Fiorito, E.; Miles, M.A.; Zelson, M. Stress recovery during exposure to natural and urban environments. *J. Environ. Psychol.* **1991**, *11*, 201–230. [CrossRef]
17. Hartig, T. Restorative Environments. *Encycl. Appl. Psychol.* **2004**, *3*, 273–279. [CrossRef]
18. Deng, L.; Li, X.; Luo, H.; Fu, E.-K.; Ma, J.; Sun, L.-X.; Huang, Z.; Cai, S.-Z.; Jia, Y. Empirical study of landscape types, landscape elements and landscape components of the urban park promoting physiological and psychological restoration. *Urban. For. Urban. Green.* **2020**, *48*, 126488. [CrossRef]
19. White, M.; Smith, A.; Humphryes, K.; Pahl, S.; Snelling, D.; Depledge, M. Blue space: The importance of water for preference, affect, and restorativeness ratings of natural and built scenes. *J. Environ. Psychol.* **2010**, *30*, 482–493. [CrossRef]
20. Li, X.; Zhang, X.; Jia, T. Humanization of nature: Testing the influences of urban park characteristics and psychological factors on collegers' perceived restoration. *Urban. For. Urban. Green.* **2023**, *79*, 127806. [CrossRef]
21. Herzog, T.R.; Colleen; Maguire, P.; Nebel, M.B. Assessing the restorative components of environments. *J. Environ. Psychol.* **2003**, *23*, 159–170. [CrossRef]
22. Huang, Q.; Yang, M.; Jane, H.-a.; Li, S.; Bauer, N. Trees, grass, or concrete? The effects of different types of environments on stress reduction. *Landsc. Urban. Plan.* **2020**, *193*, 103654. [CrossRef]
23. Wang, R.; Zhao, J.; Meitner, M.J.; Hu, Y.; Xu, X. Characteristics of urban green spaces in relation to aesthetic preference and stress recovery. *Urban. For. Urban. Green.* **2019**, *41*, 6–13. [CrossRef]
24. Honold, J.; Lakes, T.; Beyer, R.; van der Meer, E. Restoration in Urban Spaces: Nature Views from Home, Greenways, and Public Parks. *Environ. Behav.* **2015**, *48*, 796–825. [CrossRef]
25. Chang, P.-J.; Tsou, C.-W.; Li, Y.-S. Urban-greenway factors' influence on older adults' psychological well-being: A case study of Taichung, Taiwan. *Urban. For. Urban. Green.* **2020**, *49*, 126606. [CrossRef]

26. Han, B.; Li, D.; Chang, P.-J. The effect of place attachment and greenway attributes on well-being among older adults in Taiwan. *Urban. For. Urban. Green.* **2021**, *65*, 127306. [CrossRef]
27. Shan, W.; Xiu, C.; Meng, Y. How to Design Greenway on Urban Land Utilization: Linking Place Preference, Perceived Health Benefit, and Environmental Perception. *Int. J. Environ. Res. Public. Health* **2022**, *19*, 13640. [CrossRef] [PubMed]
28. Wang, R.; Browning, M.H.E.M.; Kee, F.; Hunter, R.F. Exploring mechanistic pathways linking urban green and blue space to mental wellbeing before and after urban regeneration of a greenway: Evidence from the Connswater Community Greenway, Belfast, UK. *Landsc. Urban. Plan.* **2023**, *235*, 104739. [CrossRef]
29. Li, L.; Gao, X.; Li, J.; Meng, L.; Wang, Z.; Yang, L. Difference of Usage Behavior between Urban Greenway and Suburban Greenway: A Case Study in Beijing, China. *Land* **2022**, *11*, 1245. [CrossRef]
30. Xie, B.; Lu, Y.; Wu, L.; An, Z. Dose-response effect of a large-scale greenway intervention on physical activities: The first natural experimental study in China. *Health Place* **2021**, *67*, 102502. [CrossRef]
31. Keith, S.J.; Larson, L.R.; Shafer, C.S.; Hallo, J.C.; Fernandez, M. Greenway use and preferences in diverse urban communities: Implications for trail design and management. *Landsc. Urban. Plan.* **2018**, *172*, 47–59. [CrossRef]
32. Hunter, R.F.; Adlakha, D.; Cardwell, C.; Cupples, M.E.; Donnelly, M.; Ellis, G.; Gough, A.; Hutchinson, G.; Kearney, T.; Longo, A.; et al. Investigating the physical activity, health, wellbeing, social and environmental effects of a new urban greenway: A natural experiment (the PARC study). *Int. J. Behav. Nutr. Phys. Act.* **2021**, *18*, 142. [CrossRef] [PubMed]
33. Sun, S. *Research on Urban Greenway Planning and Design*; Beijing Forestry University: Beijing, China, 2013.
34. Liao, J. *Evaluation and Research on Urban Greenway Recreation Space Landscape Based on Multidimesional Perspective—Taking Chengdu as an Example*; Southwest Jiaotong University: Chengdu, China, 2018.
35. Zhu, Y.; Dong, J.; Weng, Y.; Dong, J.; Wang, M. Audio-visual Interaction Evaluation of Forest Park Environment Based on Eye Movement Tracking Technology. *Chin. Landsc. Archit.* **2021**, *37*, 69–71. [CrossRef]
36. Weng, Y.; Zhu, Y.; Dong, J.; Wang, M.; Dong, J. Effects of Soundscape on Emotion and Attention on Campus Green Space—A Case Study of Fujian Agriculture and Forestry University. *Chin. Landsc. Archit.* **2021**, *37*, 88–93. [CrossRef]
37. van den Berg, A.E.; Koole, S.L.; van der Wulp, N.Y. Environmental preference and restoration: (How) are they related? *J. Environ. Psychol.* **2003**, *23*, 135–146. [CrossRef]
38. Van den Berg, A.E.; Jorgensen, A.; Wilson, E.R. Evaluating restoration in urban green spaces: Does setting type make a difference? *Landsc. Urban. Plan.* **2014**, *127*, 173–181. [CrossRef]
39. Meuwese, D.; Dijkstra, K.; Maas, J.; Koole, S.L. Beating the blues by viewing Green: Depressive symptoms predict greater restoration from stress and negative affect after viewing a nature video. *J. Environ. Psychol.* **2021**, *75*, 101594. [CrossRef]
40. Ulrich, R.S. Health Benefits of Gardens in Hospitals. In Proceedings of the International Exhibition Floriade 2002, Haarlemmermeer, The Netherlands, 25 April–20 October 2002.
41. *DBJ51/T097-2018*; Standard for Planning and Design of Urban and Rural Greenway in Sichuan Province. Sichuan Department of Housing and Urban-Rural Development: Chengdu, China, 2018.
42. Chang, C.-Y.; Hammitt, W.E.; Chen, P.-K.; Machnik, L.; Su, W.-C. Psychophysiological responses and restorative values of natural environments in Taiwan. *Landsc. Urban. Plan.* **2008**, *85*, 79–84. [CrossRef]
43. Gordon, A.M.; Mendes, W.B. A large-scale study of stress, emotions, and blood pressure in daily life using a digital platform. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2105573118. [CrossRef] [PubMed]
44. Hartig, T.; Kaiser, F.; Bowler, P. *Further Development of a Measure of Perceived Environmental Restorativeness (Working Paper #5)*; Institute for Housing Research: Uppsala, Sweden, 1997.
45. Kaplan, R.; Kaplan, S. *The Experience of Nature: A Psychological Perspective*; Cambridge University Press: New York, NY, USA, 1989; 340p.
46. Huang, Y.; Fu, W.; Weng, Y.; Wang, M. A Study on the Relationship between Individual Landscape Preference, Perceived Restorativeness Scale and Health Benefits Assessment of Urban Forest Pathway—A Case Study of Fudao. *Chin. Landsc. Archit.* **2020**, *36*, 73–78. [CrossRef]
47. Watson, D.; Clark, L.A.; Tellegen, A. Development and validation of brief measures of positive and negative affect: The PANAS scales. *J. Personal. Soc. Psychol.* **1988**, *54*, 1063–1070. [CrossRef]
48. Watson, D.; Clark, L.A.; Carey, G. Positive and negative affectivity and their relation to anxiety and depressive disorders. *J. Abnorm. Psychol.* **1988**, *97*, 346–353. [CrossRef]
49. Benita, F.; Tunçer, B. Exploring the effect of urban features and immediate environment on body responses. *Urban. For. Urban. Green.* **2019**, *43*, 126365. [CrossRef]
50. Panno, A.; Carrus, G.; Lafortezza, R.; Mariani, L.; Sanesi, G. Nature-based solutions to promote human resilience and wellbeing in cities during increasingly hot summers. *Environ. Res.* **2017**, *159*, 249–256. [CrossRef]
51. Malekinezhad, F.; Courtney, P.; Bin Lamit, H.; Vigani, M. Investigating the Mental Health Impacts of University Campus Green Space Through Perceived Sensory Dimensions and the Mediation Effects of Perceived Restorativeness on Restoration Experience. *Front. Public. Health* **2020**, *8*, 578241. [CrossRef] [PubMed]
52. Stigsdotter, U.K.; Corazon, S.S.; Sidenius, U.; Refshauge, A.D.; Grahn, P. Forest design for mental health promotion—Using perceived sensory dimensions to elicit restorative responses. *Landsc. Urban. Plan.* **2017**, *160*, 1–15. [CrossRef]
53. Grahn, P.; Stigsdotter, U.K. The relation between perceived sensory dimensions of urban green space and stress restoration. *Landsc. Urban. Plan.* **2010**, *94*, 264–275. [CrossRef]

54. Cao, S.; Shang, Z.; Li, X.; Luo, H.; Sun, L.; Jiang, M.; Du, J.; Fu, E.; Ma, J.; Li, N.; et al. Cloudy or sunny? Effects of different environmental types of urban green spaces on public physiological and psychological health under two weather conditions. *Front. Public. Health* **2023**, *11*, 1258848. [CrossRef] [PubMed]
55. Hooyberg, A.; Michels, N.; Allaert, J.; Vandegehuchte, M.B.; Everaert, G.; De Henauw, S.; Roose, H. 'Blue' coasts: Unravelling the perceived restorativeness of coastal environments and the influence of their components. *Landsc. Urban. Plan.* **2022**, *228*, 104551. [CrossRef]
56. Shu, Y.; Wu, C.; Zhai, Y. Impacts of Landscape Type, Viewing Distance, and Permeability on Anxiety, Depression, and Stress. *Int. J. Environ. Res. Public. Health* **2022**, *19*, 9867. [CrossRef]
57. Appleton, J. *The Experience of Landscape*; Wiley: London, UK, 1996.
58. Gatersleben, B.; Andrews, M. When walking in nature is not restorative-the role of prospect and refuge. *Health Place* **2013**, *20*, 91–101. [CrossRef]
59. White, M.P.; Pahl, S.; Wheeler, B.W.; Fleming, L.E.F.; Depledge, M.H. The 'Blue Gym': What can blue space do for you and what can you do for blue space? *J. Mar. Biol. Assoc. United Kingd.* **2016**, *96*, 5–12. [CrossRef]
60. Zhang, J.; Yang, Z.; Chen, Z.; Guo, M.; Guo, P. Optimizing Urban Forest Landscape for Better Perceptions of Positive Emotions. *Forests* **2021**, *12*, 1691. [CrossRef]
61. Volker, S.; Kistemann, T. Reprint of: "I'm always entirely happy when I'm here!" Urban blue enhancing human health and well-being in Cologne and Dusseldorf, Germany. *Soc. Sci. Med.* **2013**, *91*, 141–152. [CrossRef]
62. Katayama, T.; Hayashi, T.; Shiotsuki, Y.; Kitayama, H.; Ishii, A.; Nishida, M.; Tsutsumi, J.-I.; Oguro, M. Cooling effects of a river and sea breeze on the thermal environment in a built-up area. *Energy Build.* **1991**, *16*, 973–978. [CrossRef]
63. Murakawa, S.; Sekine, T.; Narita, K.-I.; Nishina, D. Study of the effects of a river on the thermal environment in an urban area. *Energy Build.* **1991**, *16*, 993–1001. [CrossRef]
64. Palmer, S.E.; Schloss, K.B. An ecological valence theory of human color preference. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 8877–8882. [CrossRef] [PubMed]
65. Chin, E.Y.; Kupfer, J.A. Identification of environmental drivers in urban greenway communities. *Urban. For. Urban. Green.* **2019**, *47*, 126549. [CrossRef]
66. Herzog, T.R. A cognitive analysis of preference for waterscapes. *J. Environ. Psychol.* **1985**, *5*, 225–241. [CrossRef]
67. Verhaegen, M.J.B. The Aquatic Ape Theory: Evidence and a possible scenario. *Med. Hypotheses* **1985**, *16*, 17–32. [CrossRef]
68. Aboufazeli, S.; Jahani, A.; Farahpour, M. Aesthetic quality modeling of the form of natural elements in the environment of urban parks. *Evol. Intell.* **2022**, *17*, 327–338. [CrossRef]
69. Güngör, S.; Polat, A. Relationship between visual quality and landscape characteristics in urban parks. *J. Environ. Prot. Ecol.* **2018**, *19*, 939–948.
70. Yakınlar, N.; Akpınar, A. How perceived sensory dimensions of urban green spaces are associated with adults' perceived restoration, stress, and mental health? *Urban. For. Urban. Green.* **2022**, *72*, 127572. [CrossRef]
71. Abkar, M.; Kamal, M.; Maulan, S.; Mariapan, M.; Davoodi, S.R. Relationship between the Preference and Perceived Restorative Potential of Urban Landscapes. *HortTechnology* **2011**, *21*, 514–519. [CrossRef]
72. Hartig, T. Nature experience in transactional perspective. *Landsc. Urban. Plan.* **1993**, *25*, 17–36. [CrossRef]
73. Macaulay, R.; Lee, K.; Johnson, K.; Williams, K. 'Letting my mind run wild': Exploring the role of individual engagement in nature experiences. *Urban. For. Urban. Green.* **2022**, *71*, 127566. [CrossRef]
74. Macaulay, R.; Johnson, K.; Lee, K.; Williams, K. Comparing the effect of mindful and other engagement interventions in nature on attention restoration, nature connection, and mood. *J. Environ. Psychol.* **2022**, *81*, 101813. [CrossRef]
75. Maurer, M.; Zaval, L.; Orlove, B.; Moraga, V.; Culligan, P. More than nature: Linkages between well-being and greenspace influenced by a combination of elements of nature and non-nature in a New York City urban park. *Urban. For. Urban. Green.* **2021**, *61*, 127081. [CrossRef]
76. Samus, A.; Freeman, C.; Dickinson, K.J.M.; van Heezik, Y. Relationships between nature connectedness, biodiversity of private gardens, and mental well-being during the COVID-19 lockdown. *Urban. For. Urban. Green.* **2022**, *69*, 127519. [CrossRef]
77. Deng, L.; Luo, H.; Ma, J.; Huang, Z.; Sun, L.-X.; Jiang, M.-Y.; Zhu, C.-Y.; Li, X. Effects of integration between visual stimuli and auditory stimuli on restorative potential and aesthetic preference in urban green spaces. *Urban. For. Urban. Green.* **2020**, *53*, 126702. [CrossRef]
78. Samus, A.; Freeman, C.; van Heezik, Y.; Krumme, K.; Dickinson, K.J.M. How do urban green spaces increase well-being? The role of perceived wildness and nature connectedness. *J. Environ. Psychol.* **2022**, *82*, 101850. [CrossRef]
79. Angold, P.G.; Sadler, J.P.; Hill, M.O.; Pullin, A.; Rushton, S.; Austin, K.; Small, E.; Wood, B.; Wadsworth, R.; Sanderson, R.; et al. Biodiversity in urban habitat patches. *Sci. Total Environ.* **2006**, *360*, 196–204. [CrossRef] [PubMed]
80. Carlier, J.; Moran, J. Landscape typology and ecological connectivity assessment to inform Greenway design. *Sci. Total Environ.* **2019**, *651*, 3241–3252. [CrossRef]
81. O'Sullivan, O.S.; Holt, A.R.; Warren, P.H.; Evans, K.L. Optimising UK urban road verge contributions to biodiversity and ecosystem services with cost-effective management. *J. Environ. Manag.* **2017**, *191*, 162–171. [CrossRef]
82. Ulrich, R. *Biophilic Theory and Research for Healthcare Design*; John Wiley: Hoboken, NJ, USA, 2008; pp. 87–106.

83. Carrus, G.; Scopelliti, M.; Lafortezza, R.; Colangelo, G.; Ferrini, F.; Salbitano, F.; Agrimi, M.; Portoghesi, L.; Semenzato, P.; Sanesi, G. Go greener, feel better? The positive effects of biodiversity on the well-being of individuals visiting urban and peri-urban green areas. *Landsc. Urban. Plan.* **2015**, *134*, 221–228. [CrossRef]
84. Wilson, E.O. *Biophilia*; Harvard University Press: Cambridge, MA, USA, 1986.
85. Wang, R.; Feng, Z.; Pearce, J.; Liu, Y.; Dong, G. Are greenspace quantity and quality associated with mental health through different mechanisms in Guangzhou, China: A comparison study using street view data. *Environ. Pollut.* **2021**, *290*, 117976. [CrossRef] [PubMed]
86. Wu, L.; Dong, Q.; Luo, S.; Jiang, W.; Hao, M.; Chen, Q. Effects of Spatial Elements of Urban Landscape Forests on the Restoration Potential and Preference of Adolescents. *Land* **2021**, *10*, 1349. [CrossRef]
87. Luo, S.; Xie, J.; Furuya, K. Assessing the Preference and Restorative Potential of Urban Park Blue Space. *Land* **2021**, *10*, 1233. [CrossRef]
88. Yamashita, S. Perception and evaluation of water in landscape: Use of Photo-Projective Method to compare child and adult residents' perceptions of a Japanese river environment. *Landsc. Urban. Plan.* **2002**, *62*, 3–17. [CrossRef]
89. Bogar, S.; Beyer, K.M. Green space, violence, and crime: A systematic review. *Trauma Violence Abus.* **2016**, *17*, 160–171. [CrossRef]
90. Stigsdotter, U.K.; Ekholm, O.; Schipperijn, J.; Toftager, M.; Kamper-Jorgensen, F.; Randrup, T.B. Health promoting outdoor environments—Associations between green space, and health, health-related quality of life and stress based on a Danish national representative survey. *Scand. J. Public. Health* **2010**, *38*, 411–417. [CrossRef]
91. Fishbein, M.; Ajzen, I. Belief, attitude, intention and behavior: An introduction to theory and research. *Contemp. Sociol.* **1977**, *6*, 244.
92. Ajzen, I.; Driver, B.L. Application of the Theory of Planned Behavior to Leisure Choice. *J. Leis. Res.* **1992**, *24*, 207–224. [CrossRef]
93. Chen, R.; Gao, Y.; Zhang, R.; Zhang, Z.; Zhang, W.; Meng, H.; Zhang, T. How Does the Experience of Forest Recreation Spaces in Different Seasons Affect the Physical and Mental Recovery of Users? *Int. J. Environ. Res. Public. Health* **2023**, *20*, 2357. [CrossRef] [PubMed]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# Ecological Vulnerability Assessment and Spatiotemporal Characteristics Analysis of Urban Green-Space Systems in Beijing–Tianjin–Hebei Region

**Xiangyu Fu [1,2,3,4] and Yajing Liu [1,2,3,4,*]**

[1] College of Mining Engineering, North China University of Science and Technology, Tangshan 063210, China; mailfxy97@163.com
[2] Tangshan Key Laboratory of Resources and Environmental Remote Sensing, Tangshan 063210, China
[3] Hebei Industrial Technology Institute of Mine Ecological Remediation, Tangshan 063210, China
[4] Hebei Key Laboratory of Mining Development and Security Technology, Tangshan 063210, China
* Correspondence: lyj2206@126.com

**Abstract:** The evaluation and analysis of the ecological vulnerability of urban green-space systems are conducive to the sustainable development of urban green-space systems. Taking the urban green-space system in the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020 as the research object, an ESSR model was first constructed, and a total of ten types of impact factors were integrated into the four dimensions of "Exposure, Sensitivity, State and Response". The weight of the impact factors was objectively determined via spatial principal component analysis, and the ecological vulnerability of the urban green-space system was evaluated via superposition analysis; the evaluation's results were graded. Moreover, the transfer matrix, center-of-gravity migration model, standard deviation ellipse, and spatial autocorrelation analysis were used to study the temporal and spatial variation characteristics of the evaluation results; then, the driving force of impact factors was analyzed based on a geographical detector. Finally, the rationality of the evaluation results was verified using the changing trend of the remote sensing ecological index (RSEI). The results show that the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region has decreased year by year for the past ten years. The distribution law of "Hebei surrounds Beijing and Tianjin" is presented in this space, and 2015 is the mutation node. In 2010, the moderately and severely vulnerable areas of Hebei surrounded the mildly vulnerability areas of Beijing and Tianjin. Moreover, in 2015 and 2020, the mildly vulnerable areas of Hebei surrounded the severely vulnerable areas of Beijing and Tianjin. Vulnerability expands slightly in the east–west direction and shrinks slightly in the north–south direction, and the center of gravity shifts towards Beijing year by year along the northeast direction. Moreover, the spatial distribution of vulnerability shows significant positive spatial autocorrelations and exhibits very obvious agglomeration. In addition, vulnerability is the result of the combined effect of various factors, and education degree, human disturbance index, and annual average precipitation are the dominant factors. The analysis results provide a reference for the effective application and sustainable development of urban green-space ecological functions.

**Keywords:** Beijing–Tianjin–Hebei region; urban green-space system; ecological vulnerability assessment; ESSR model; sustainability

**Citation:** Fu, X.; Liu, Y. Ecological Vulnerability Assessment and Spatiotemporal Characteristics Analysis of Urban Green-Space Systems in Beijing–Tianjin–Hebei Region. *Sustainability* **2024**, *16*, 2289. https://doi.org/10.3390/su16062289

Academic Editors: Xin-Chen Hong, Baojie He, Jiang Liu, Jinda Qi, Guangyu Wang and Shi Cheng

Received: 25 December 2023
Revised: 5 March 2024
Accepted: 8 March 2024
Published: 9 March 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

With the rapid expansion of the city, urban green spaces are decreasing, and urban development and human activity require substantial urban green space, which makes the contradiction between the supply and demand of urban green spaces increasingly prominent. As one of the important components of the urban ecosystem, the urban green-space system can effectively reduce the serious constraints of the urbanization process on the urban–ecological environment, which is conducive to human physical and mental

health [1,2], and it plays a positive role in restoring the urban environment, protecting the diversity of urban species, and improving the urban heat-island effect. Therefore, this study deeply explores the urban green space and analyzes its ecological vulnerability. The research results are conducive to further alleviating the contradiction between the supply and demand of urban green space [3–5].

In recent years, some scholars have mainly studied the social service function of urban green-space systems. Through the study of urban green-space planning and development, Covadonga et al. [6] identified the most critical factors affecting the sustainable development of urban societies and ecology. Lydia et al. [7] studied the correlation between urban green space and residents' life satisfaction. Shishir et al. [8] supported the future master plan for urban green spaces by formulating sustainable management policies for them. Syrbe et al. [9] raised the supply of urban green spaces to a strategic level. Other scholars' research on urban green-space systems mainly focuses on ecological benefit evaluation, landscape-quantity evaluation, and the comprehensive evaluation of green-space systems. Yeonsu et al. [10] studied the ecological benefits of urban green-space systems from the perspective of carbon storage in urban green spaces. In terms of landscape quantity evaluation, the main research indicators are also based on the per capita green area, green rate, and green landscape pattern. In the comprehensive evaluation of urban green spaces, "3S" technology is mainly used, combined with the evaluation model, and factors such as the number and area of green spaces are considered to evaluate the urban green-space system. These include economic benefit evaluation [11], emergency disaster-prevention evaluation [12], and social-service-function evaluation [13].

Based on existing research results, research on urban green-space systems still has the following shortcomings. First of all, with respect to current research on urban green-space systems, it emphasizes the value and role of urban green-space systems in contributing to human society but ignores the disturbance and influence of natural factors and human social factors on urban green-space systems. Secondly, under the influence of natural and human factors, urban green-space systems will show different degrees of vulnerability. The fragile urban green-space ecosystem is not only threatened by sustainable development but it is also limited in value. Therefore, the ecological vulnerability assessment of urban green-space systems not only helps people correctly understand green spaces, but also provides important theoretical support for the effective application and sustainable development of urban green spaces' ecological functions [14].

Based on the above shortcomings, this study constructs an ESSR "Exposure–Sensitivity–State–Response" model for the vulnerability of the urban green-space ecosystem in the Beijing–Tianjin–Hebei region, and it combines natural, social, and human factors to select influencing factors. The spatial principal component analysis method is used to objectively determine the weight of the factors, and GIS overlay analyses are used to quantitatively classify vulnerability to construct an urban green-space ecological evaluation index system and quantitatively measure the ecological vulnerability of urban green spaces. Furthermore, the development status of the urban green space in the Beijing–Tianjin–Hebei region is analyzed using a transfer matrix, spatial autocorrelation, standard deviation ellipse, center-of-gravity migration model, geographical detector, and other methods in order to explore the spatial and temporal distribution of ecological vulnerability in the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020. Its impact factors are analyzed thoroughly, revealing the main factors affecting the spatial pattern, in order to provide references for urban green-space planning and urban ecological sustainable development strategies for the Beijing–Tianjin–Hebei region.

## 2. Materials and Methods

### *2.1. Methodological Design Flow*

Figure 1 shows the details of this study (Figure 1), which includes five parts: ESSR assessment system, ecological vulnerability assessment, spatio-temporal changes in eco-

logical vulnerability, ecological vulnerability impact factors, and ecological vulnerability-assessment result tests.

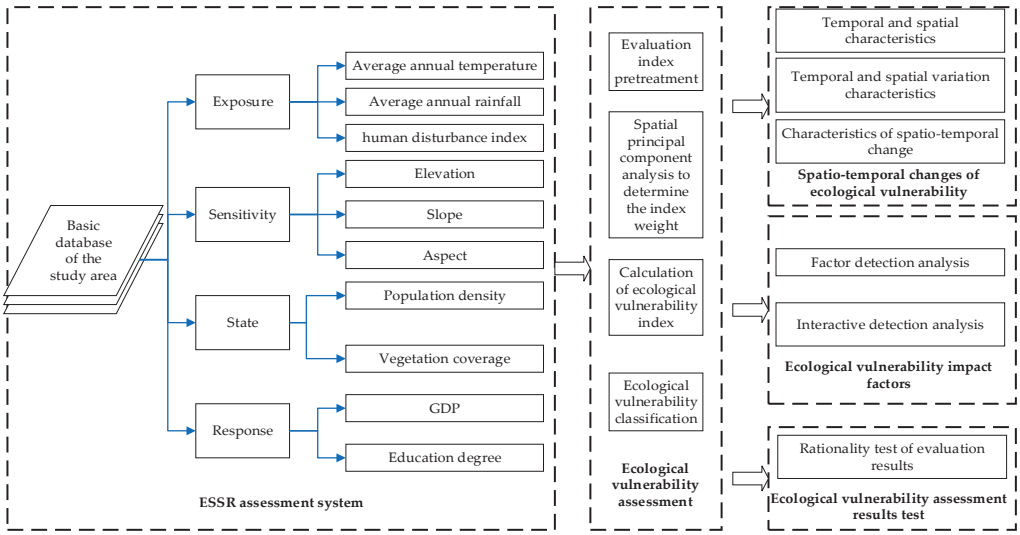



**Figure 1.** The framework of the research idea and methodology.

## 2.2. Study Area

The Beijing–Tianjin–Hebei urban agglomeration, which is located in the northern part of the North China Plain, comprises the third step of China's terrain. It is China's "capital economic circle" and the most important political, cultural, and economic core area in China.

Its geographical range is within 36°05′ N~42°37′ N, 113°27′ E~119°50′ E, its altitude is below 3000 m, its average annual precipitation is 400~800 mm, and the average temperature is 12 °C. The total area of the Beijing–Tianjin–Hebei region is 216,000 km$^2$, and the regional topography is complex and diverse. In 2020, the population of the Beijing–Tianjin–Hebei region reached 112.7 million, and the total GDP reached CNY 8.6 trillion. The level of urbanization is high but the ecological environment is overloaded. Thanks to several major ecological construction projects such as the Three North Shelterbelt, the regional ecological environment quality has improved in recent years, and the ecological degradation rate has slowed down (Figure 2).

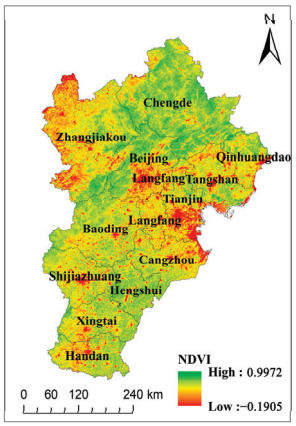



**Figure 2.** The boundaries of the Beijing–Tianjin–Hebei urban agglomeration.

## 2.3. Data Collection and Processing

The research data mainly include the remote sensing data, meteorological data, socio-economic data, etc., of the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020.

Remote sensing data include the normalized difference vegetation index (NDVI) and NPP/VIIRS night-time light data. NDVI data were obtained from MOD13Q data, and

the set was downloaded from the EarthData website (https://search.earthdata.nasa.gov/ (accessed on 10 May 2023)). The maximum NDVI value of each year was calculated using the maximum synthesis method. NPP/VIIRS night-time light data from the Earth Observation Group were used (https://eogdata.mines.edu/products/vnl/ (accessed on 12 May 2023)), which belong to the National Environmental Information Center of the National Oceanic and Atmospheric Administration (NOAA) of the United States. The data were obtained for the spatialization of GDP data. Due to the lack of 2010 data, the data were replaced by 2012 data.

Meteorological data, including annual average precipitation and annual average temperature, were obtained from the National Earth System Science Data Sharing Service Platform—Loess Plateau Science Data Center (http://www.geodata.cn/data/ (accessed on 10 May 2023)).

Terrain data are mainly based on digital elevation model (DEM) data. The data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/ (accessed on 15 May 2023)), and they were divided according to administrative divisions using software. Based on the digital elevation model data, the slope and aspect data were calculated using the spatial-analysis function of the software.

Socioeconomic data include the human disturbance index, population density, and education degree. The human disturbance index was calculated from the annual land cover dataset of China, which was produced by Yang Jie and Huang Xin of Wuhan University based on Landsat images [15]. Population density data were obtained from the Distributed Active Archiving Center (DAAC) (https://sedac.ciesin.columbia.edu/ (accessed on 12 May 2023)) in the Socioeconomic Data and Applications Center (SEDAC) and Information System (EOSDIS) of the National Aeronautics and Space Administration (NASA) of the United States. The education degrees obtained from the statistical yearbooks of provinces and cities from 2010 to 2020. In order to facilitate subsequent calculations, the coordinate system of the data was finally unified as the WGS_1984_Albers projection coordinate system, and accuracy was unified to 1 km.

### *2.4. Methods*

#### 2.4.1. ESSR Model

The ecological vulnerability of the urban green-space system is a comprehensive representation of the degree of disturbance caused by the environment and society relative to urban green-space ecosystems, the sensitivity of urban green-space ecosystems to external stress or pressure, the state of an urban green-space system at a specific time, and the preventive behavior formulated by government departments for stable development.

Due to the rapid development of the Beijing–Tianjin–Hebei urban agglomeration, problems caused by human disturbances, such as increased population and accelerated urbanization, gradually emerged [16]. Coupled with the impact of climate change, these factors have exposed the green-space system to substantial external pressures. In addition, the urban agglomeration comprises a large number of cities of different natures, types, and scales that fall within a specific range, also rendering the urban agglomeration one of the most sensitive areas of the ecological environment. Therefore, its sensitivity will determine the impact of external pressure on the urban green-space system; exposure and sensitivity together produce a potential pressure source that affects the ecological vulnerability of the urban green-space system. In the face of potential pressure sources, the final impact of the urban green-space system can be determined by the state of the system itself and the corresponding action of the government.

Therefore, this study fully considers the comprehensive characterization of the ecological vulnerability of the urban green-space system. From the perspective of the generation and final impact of the pressure source, the characteristics of the urban green-space system are integrated, and the exposure and sensitivity of the VSD (exposure, sensitivity, and adaptability) model are introduced. This improves the problem that the PSR model (pressure, state, and response) ignores, which is the importance of exposure to the structure and function of the urban green-space system, and it emphasizes the sensitivity of the ecological

vulnerability of the urban green-space system relative to its structural composition for disaster stress [17]. Using a combination of the exposure and sensitivity dimensions of the VSD model, the potential impact of the pressure source is defined. The state and response dimensions of the PSR model are retained to explain the final impact of the pressure source [18]. The model is further expanded to four dimensions. From the perspective of the pressure source, the state and sensitivity of the urban green-space system, the exposure response process and the final vulnerability results are comprehensively considered. The consideration draws on the advantages of the hierarchical organization method and clear process specification of the VSD model [19]. Simultaneously, it retains the advantages of the PSR model and embeds causal logic thinking [20]. Based on the two models, this study proposes the "Exposure-Sensitivity-State-Response" ESSR model. The interaction of the four dimensions of the model constitutes the logical relationship of "what happened, the size of the impact, the results produced, and how to deal with it", as shown in Figure 3.

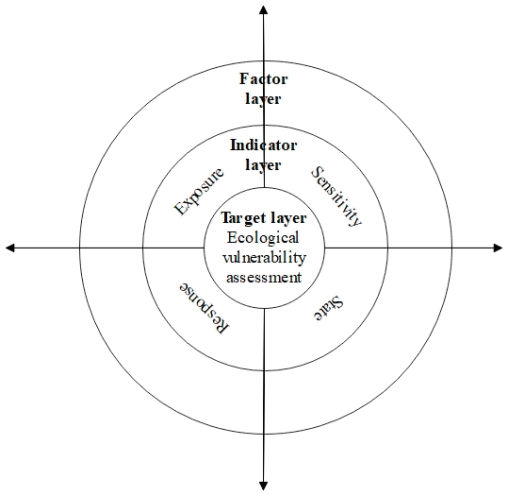



**Figure 3.** The architecture of the ESSR model.

2.4.2. ESSR Evaluation Model Index System

The research method of the ecological vulnerability evaluation index system of urban green-space systems should first be based on the ESSR model in order to explore the main impact factors affecting the ecological vulnerability of the urban green-space system. The selection of the ecological vulnerability impact factors of the urban green-space system in the Beijing–Tianjin–Hebei region is based on five principles: being scientific, systematic, comprehensive, applicable, and regional. Currently, in the study of the urban green-space ecosystem, related research on ecological vulnerability is scarce. Therefore, based on referring to international vulnerability models and assessment frameworks, this study draws on the relevant literature on urban ecological vulnerability index systems [21,22], as well as the ecological vulnerability index system of an urban green-space system, reported by Zhang et al. The concept and framework of urban vulnerability in China [23], the conceptual framework of regional ecological sustainability assessment based on the PSR model [24], and the framework of ecosystem vulnerability in semi-arid areas based on the VSD model [25] are used as references. Based on the analysis of the model's framework, the natural and social factors of the study area and the development law of the research object are fully considered. After combing and analyzing the frequency, applicability, and accessibility of different impact factors in many studies, impact factors were selected from the perspective of scientificity and objectivity [26]. At the same time, the selection of factors should also include natural, social, and human factors, in order to ensure that the impact factors can comprehensively evaluate the ecological vulnerability of the research object. In summary, the index system constructed based on the ESSR model is divided into the goal layer, the indicator layer, and the factor layer. The goal layer is the first level, the purpose of the evaluation is controlled from the core, and the evaluation results of the ecological

vulnerability of the urban green-space system in Beijing, Tianjin, and Hebei are expressed. The indicator layer comprises the second level, which explains the evolution of ecological vulnerability relative to four dimensions: exposure, sensitivity, state, and response. The factor layer comprises the third level, and it is mainly the impact factor of the ecological vulnerability assessment of the Beijing–Tianjin–Hebei urban green-space system.

Exposure refers to the degree of the interference of environmental and social pressure on the urban green-space system, which is a parameter reflecting the degree of interference or stress from the outside world. The impact factors of exposure include annual average temperatures, annual average precipitation, and the human disturbance index. The annual average temperature (Figure 4a) is a direct reflection of whether the study area is suitable for the development of the urban green-space ecosystem. The higher the annual average temperature, the lower the ecological vulnerability of the urban green-space system. Annual average precipitation (Figure 4b) reflects the meteorological and hydrological conditions in the study area. As annual average precipitation increases, the ecological vulnerability of the urban green-space system will decrease with the increase in water resources introduced by precipitation. The human disturbance index (Figure 4c) is the expression of the disturbance degree of human activities to the urban green-space-system ecosystem [27,28].

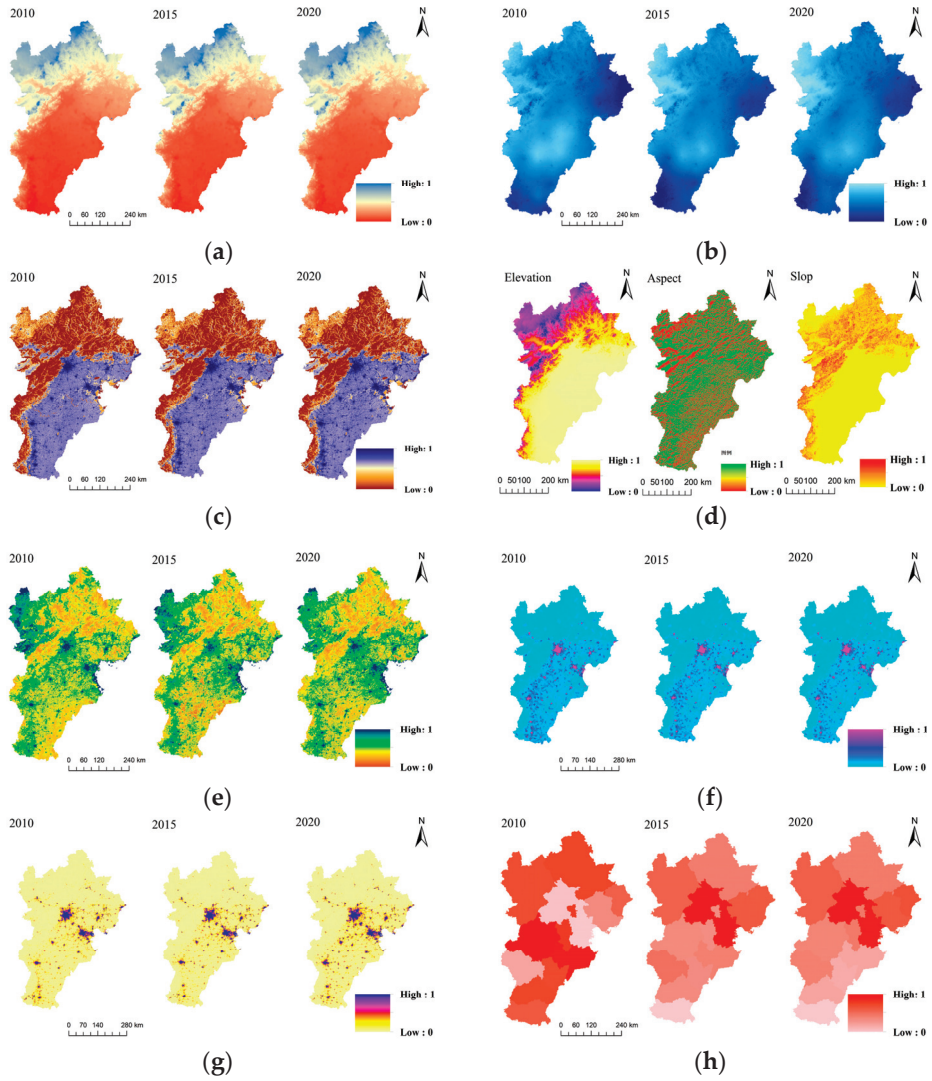



**Figure 4.** The impact factors of the ecological vulnerability assessment of the urban green-space system in the Beijing–Tianjin–Hebei region. (**a**) The annual average temperature. (**b**) The annual average precipitation. (**c**) The human disturbance index. (**d**) The digital elevation model, aspect, and slope. (**e**) The vegetation coverage. (**f**) The population density. (**g**) GDP. (**h**) The education degree.

Sensitivity is a measure of the degree of difficulty between the stress and the consequences of the urban green-space system. Sensitivity is related to the critical conditions of the destruction of the urban green-space system. It can be reflected by natural resource conditions and topographic features. Among them, topographic features are the basis of ecological environment sensitivity (Figure 4d) [29]: the digital elevation model is one of the important topographic factors. By observing the digital elevation model, human disturbance relative to the urban green-space system is becoming increasingly obvious. Moreover, the slope is an important factor in measuring the influence of the natural environment on the urban green-space system. The larger the slope, the more unfavorable it is to the development of a green-space system. Finally, the aspect represents the southerly area, which experiences substantial amounts of light, the rapid evaporation of water, and frequent human activities; thus, the vulnerability of the urban green-space system will be higher.

The state indicates the state of the urban green-space system when subjected to natural and human pressures [30]. It includes the state of the urban green-space system after experiencing changes, as well as other changes that occur in the state of the urban green-space system after the initial change. Therefore, the state factors include two impact factors: population density and vegetation coverage. Vegetation coverage (Figure 4e) represents the state of the urban green space ecosystem, and vegetation coverage is directly related to the ecological vulnerability of the urban green-space system. Moreover, it exhibits a negative correlation: the higher the vegetation coverage, the lower the ecological vulnerability of the green-space system [31]. Population density represents the state of human life (Figure 4f). The change in the urban green-space system may lead to the emergence of the urban ecological problems, the deterioration of ecological environment, and the introduction of impacts on human living conditions; moreover, changes may also cause reactions in the urban green-space system.

Response refers to the possible impact on the natural environment and human behavior. In this study, government departments formulate mitigation or solutions for the stable development of the urban green-space system [32]. Using GDP and residents' education degrees, GDP (Figure 4g) is an important criterion for measuring the quality of social and economic development. The higher the GDP, the better the social and economic benefits; the greater the government's financial investment in protecting the environment, the lower the ecological vulnerability of the urban green-space system [33]. The education degree (Figure 4h) refers to the government's and individual's behavior in improving the cultural level and raising awareness of ecological protection through education in order to reduce or prevent the destruction of the ecological environment. It is generally believed that the higher the degree of education, the lower the ecological vulnerability [34].

#### 2.4.3. Index Weight Calculation of ESSR Model

1. Standardized Treatment of Impact Factors

In order to solve the dimension problem of the impact factors of the ecological vulnerability evaluation index data of the urban green-space system, range standardization was carried out [35]. In addition, there are two types of impact factors in the index. One is the positive impact factor. Such indicators are generally considered to be better when their values are greater, and Formula (1) is used for their calculations. There is also a class of negative impact factors. Such indicators are generally required to be as low in value as possible, and Formula (2) is used for their calculations. The formulas are as follows:

$$M_{ij} = \frac{Y_{ij} - \min(Y_{ij})}{\max(Y_{ij}) - \min(Y_{ij})} \quad (1)$$

$$M'_{ij} = \frac{\max(Y_{ij}) - Y_{ij}}{\max(Y_{ij}) - \min(Y_{ij})} \quad (2)$$

In the above formulas, $Y_{ij}$, $M_{ij}$, and $M'_{ij}$ are the original value and standardized value of the $j$ index in the $i$ year; max ($Y_{ij}$) and min ($Y_{ij}$) are the maximum and minimum values of index $j$, respectively.

2. Principal Component Analysis

Firstly, the cumulative contribution rate of each impact factor is calculated using Formula (3) via the feature vector of the impact factor. The cumulative contribution rate is used to determine the number of main factors in the evaluation. When the cumulative contribution rate exceeds 90%, the number of main factors is determined [36].

$$a_i = \lambda_i / \sum_{i=1}^{m} \lambda_i \tag{3}$$

In the formula, $\lambda$ is the eigenvector value.

When the number of main factors is determined, the variance of common factors is calculated according to Formula (4).

$$H_j = \sum_{k=1}^{m} \lambda_{jk}^2 \tag{4}$$

In the formula, $H_j$ is the common factor variance; m is the number of principal factors; $\lambda^2{}_{jk}$ is the eigenvalue of factor j relative to principal component k. In this study, $m$ = 9 and $j$ = 10. Finally, the weight of each evaluation index can be obtained using Formula (5):

$$p_i = w_j = H_j / \sum_{j=1}^{10} H_j \tag{5}$$

In the formula, $w_j$ is the relative weight of evaluation index $j$. The results are shown in Table 1.

**Table 1.** Index system and weight of the ESSR model.

| Goal Layer | Indicator Layer | Factor Layer | Positive (+) or Negative (−) | Factor Weight in 2010 | Factor Weight in 2015 | Factor Weight in 2020 |
|---|---|---|---|---|---|---|
| Ecological vulnerability assessment of the urban green-space system in Beijing–Tianjin–Hebei | Exposure | Annual average temperature | − | 0.142 | 0.125 | 0.125 |
| | | Annual average precipitation | − | 0.134 | 0.125 | 0.125 |
| | | Human disturbance index | + | 0.143 | 0.125 | 0.125 |
| | Sensitivity | Digital elevation model | − | 0.045 | 0.109 | 0.107 |
| | | Aspect | + | 0.006 | 0.014 | 0.017 |
| | | Slope | + | 0.143 | 0.125 | 0.125 |
| | State | Population density | + | 0.005 | 0.009 | 0.008 |
| | | Vegetation coverage | − | 0.143 | 0.125 | 0.125 |
| | Response | GDP | − | 0.109 | 0.118 | 0.118 |
| | | Education degree | − | 0.130 | 0.125 | 0.125 |

2.4.4. Ecological Vulnerability Classification of the Urban Green-Space System

This is based on the domestic and international ecological vulnerability-rating criteria, combined with the actual characteristics of the Beijing–Tianjin–Hebei urban green-space system. The study used the natural breakpoint method to classify the ecological vulnerability index of the Beijing–Tianjin–Hebei urban green-space system in 2010, 2015, and 2020. The average value of the breakpoints in three years was taken as the classification basis, and the ecological environment's vulnerability was divided into five grades—slight vulnerability, mild vulnerability, moderate vulnerability, severe vulnerability, and extreme vulnerability [37]—which ensured the comparability of the evaluation results, as shown in Table 2.

**Table 2.** The classification of ecological vulnerability-assessment results of the urban green-space system in the Beijing–Tianjin–Hebei region.

| Vulnerability Degree | Grade | Vulnerability Index | Ecological Character |
|---|---|---|---|
| Slightly vulnerable | I | <0.334 | Exposure and sensitivity are extremely low; the green-space system is in good condition; and social response is timely. It exhibits strong resistance when encountering internal and external pressure. |
| Mildly vulnerable | II | 0.334–0.399 | Slight exposure and sensitivity; the state of the green-space ecosystem is generally fine; and social response is timelier. When encountering internal and external pressure, it exhibits strong resistance. |
| Moderately vulnerable | III | 0.399–0.458 | Has a certain degree of exposure and sensitivity; the state of the green-space ecosystem is poor; and social response is slow. It exhibits weak resistance when encountering internal and external pressure. |
| Severely vulnerable | IV | 0.458–0.523 | It has high exposure and sensitivity; the state of the green-space ecosystem is very poor; and social response is slow. When encountering internal and external pressure, it has a weak resistance. |
| Extremely vulnerable | V | >0.523 | It has extremely high exposure and sensitivity; the state of the green-space ecosystem is bad; and social response is very slow. When faced with internal and external pressure, these areas do not have the ability to resist. |

#### 2.4.5. Spatio-Temporal Evolution Analysis Method of the Ecological Vulnerability of the Urban Green-Space System

1. Transfer Matrix

The transfer matrix can accurately quantify the transfer between states in the system during the research period. It can comprehensively and meticulously analyze the change characteristics with respect to the urban green-space system's ecological vulnerability, which is the basis for studying the structural change, and the directional change of the ecological vulnerability of the urban green-space system. According to the ecological vulnerability changes in the urban green-space system of Beijing–Tianjin–Hebei during different periods, a two-dimensional matrix was obtained. Carrying out an analysis of the two-dimensional matrix, the mutual transformation between the vulnerability degrees of the two periods can be obtained.

2. Standard Deviation Ellipse and Center-of-Gravity Migration Model

As one of the spatial statistical methods [38], the standard deviation ellipse can quantitatively explains the centrality, directionality, and expansion direction deviation of the urban green-space ecosystem's vulnerability. The center-of-gravity migration model can reflect the moving direction and distance of the ecological vulnerability gravity center of the urban green-space system, and it can reflect the change range and spatial difference of a certain geographical element within a certain period of time.

3. Spatial Autocorrelation Analysis

Spatial autocorrelation refers to the phenomenon that similar phenomena or objects in space show similar characteristics [39], and this is also observed in global and local hypothesis tests.

Global spatial autocorrelation is usually used to test the spatial pattern of the ecological vulnerability of urban green-space systems throughout the study area. It is usually calculated using global Moran's I, and the formula is as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\right)\left(\sum_{i=1}^{n} x_i - \overline{x}\right)^2} \quad (6)$$

In the formula, $n$ is the number of spatial units involved in the analysis, $x_i$ and $x_j$ are the observed values of a certain attribute on space units $i$ and $j$, respectively; $x$ is the average value of a certain attribute in each space; $W_{ij}$ is the spatial weight matrix; and $I$ is the global spatial autocorrelation coefficient Moran's I.

The local Moran's I is the decomposition of the global Moran's I in each spatial unit, which can accurately reflect and grasp the aggregation and differentiation characteristics of spatial and adjacent units, and it highlights the aggregation state of the local ecological vulnerability areas of the urban green-space system. The formula is as follows:

$$I_i = \frac{(x_i - \overline{x})\sum_{j=1}^{n} w_{ij}(x_j - \overline{x})}{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad (7)$$

In the formula, $x_i$ and $x_j$ are the observed values of an attribute on space units $i$ and $j$, respectively; $x$ is the average value of an attribute in each space; $\boldsymbol{w_{ij}}$ is the spatial weight matrix; and $I_i$ represents the local Moran's I.

4. Geographical Detector

In this study, the single-factor and interactive detectors in the geographic detector [40,41] were used to quantitatively analyze the influencing factors of the spatial distribution of ecological vulnerability in the urban green-space system of the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020. The single-factor detector can quantify the spatial and temporal variation of ecological vulnerability between different independent variables, and it can detect the degree and size of its impact. The formula is as follows:

$$\mathrm{q} = 1 - \frac{\sum_{\mathrm{h}=1}^{L} N_{\mathrm{h}}\sigma_{\mathrm{h}}^2}{N\sigma^2} \quad (8)$$

In the formula, $N$ = 1, 2. . ., for a specific type; $L$ is the stratification of variable X or factor Y: that is, the classification or partition; $N_h$ is the number of elements in layer h; and $\sigma_h$ and σ are the variance of class h and the variance of the entire region, respectively. The range of q is [0, 1]. The larger the q value, the better independent variable X explains the change in ecological vulnerability Y, and vice versa is true as well.

The interaction detector is used to determine the interaction between different impact factors: that is, whether the interaction of evaluation factors will change its explanatory power to the ecological vulnerability index.

## 3. Results

### *3.1. The General Characteristics of the Spatial and Temporal Changes of the Ecological Vulnerability of the Urban Green-Space System in the Beijing–Tianjin–Hebei Region*

#### 3.1.1. Spatial and Temporal Distribution Characteristics of Ecological Vulnerability

The ecological vulnerability index of the urban green-space system in the study area in 2010, 2015, and 2020 was calculated using the ecological-vulnerability assessment method. The spatial distribution map of ecological vulnerability in the study area was obtained using the

ecological-vulnerability classification method, and the results of different vulnerability levels within each period and the comprehensive index of ecological vulnerability were obtained.

The statistical results show that the average ecological vulnerability of the study area in 2010, 2015, and 2020 is 0.457075, 0.42809, and 0.422939, respectively. The larger the average value, the more fragile the overall ecology of the urban green-space system in the study area, and the poorer the ecological environment. The ecological vulnerability value of the urban green-space system in this study exhibited a steady downward trend. In terms of the proportion of each graded area, taking 2020 as an example, slight vulnerability, mild vulnerability, moderate vulnerability, severe vulnerability, and extreme vulnerability account for 14%, 23%, 30%, 23%, and 10% of the total study area, respectively. Among them, the areas of mild vulnerability, moderate vulnerability, and severe vulnerability account for 76% of the total area. In terms of the area change of each grade, the area of the extremely vulnerable area decreased rapidly from 42,885 $km^2$ in 2010 to 21,038 $km^2$ in 2020. The area of mildly vulnerable areas has increased steadily, from 11,515 $km^2$ in 2010 to 29,662 $km^2$ in 2020 (Figure 5). This is mainly closely related to the policy changes in the Beijing–Tianjin–Hebei region. In 2010, the "Beijing–Tianjin–Hebei metropolitan area regional planning" and other policies were proposed, which resulted in the further rapid development of the region's economy, and disturbances to the environment increased. Since the 18th National Congress of the Communist Party of China, the construction of ecological civilizations was gradually promoted. With the implementation of policies such as the "Beijing–Tianjin–Hebei Collaborative Development Program" and the "Beijing–Tianjin–Hebei Collaborative Development Ecological Environment Protection Plan", Beijing–Tianjin–Hebei cities have invested heavily in ecological environment construction, resulting in a lower ecological vulnerability index in 2020 than that in 2010, and the ecological environment gradually improved. In general, from 2010 to 2020, the area of ecologically fragile areas exhibited a decreasing trend, and ecological vulnerability improved.

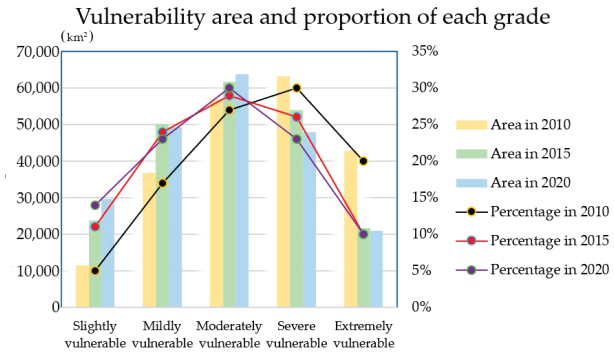



**Figure 5.** The vulnerability area and proportion of each grade.

From the perspective of spatial patterns, the ecological vulnerability of the study area has exhibited different spatial distributions in the past ten years, but the vulnerability characteristics are obvious, indicating that the ecological vulnerability of the Beijing–Tianjin–Hebei green-space system has a strong dependence on the urban distribution pattern. On the whole, the ecological vulnerability of the Beijing–Tianjin–Hebei region shows the following distribution law: "Hebei surrounds Beijing and Tianjin". In 2010, the ecological vulnerability of the Beijing–Tianjin–Hebei green-space system showed that the moderately and severely vulnerable areas of Hebei surrounded the mildly vulnerable areas of Beijing and Tianjin. The 2015 and 2020 distributions of mildly vulnerable areas in Hebei Province around severely vulnerable Beijing–Tianjin areas were observed. The slightly vulnerable and mildly vulnerable areas were mainly distributed in Beijing and Tianjin in 2010, and they were mainly distributed in Hebei Province in 2015 and 2020. The severely and extremely vulnerable areas changed from being mainly distributed in Hebei in 2010 to being mainly distributed in Beijing and Tianjin in 2015 and 2020 (Figure 6). This fully reflects the importance and development of the ecological environment in the Beijing–Tianjin–Hebei

region since the "Beijing–Tianjin–Hebei Collaborative Development Outline" was put forward in 2014, when the effective construction of Hebei Province was the ecological environment-support area of the region.

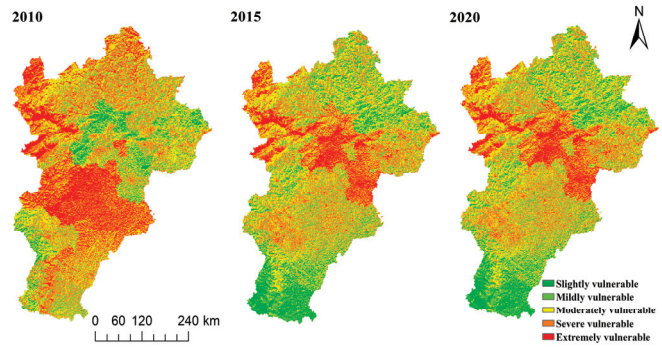



**Figure 6.** Spatial distribution of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region.

3.1.2. Spatiotemporal Evolution Characteristics of Ecological Vulnerability

According to the classification results of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region, the vulnerability transfer matrix of 2010, 2015, and 2020 was obtained using the superposition analysis function of the software. The 2010 transfer-out and 2015 transfer-in data are shown in the figure. Combined with Figures 7 and 8, it can be observed that the ecological vulnerability levels of the urban green-space system change frequently. In 2010, ecological vulnerability at all levels was transferred out of a total of 155,782 $km^2$, of which the severely and extremely vulnerable areas comprised the largest ones, with a total of 60,108 $km^2$ transferred out, accounting for 38% of the total area transferred out, mainly transferred to mildly and moderately vulnerable areas. In 2015, slightly vulnerable and mildly vulnerable areas accounted for the largest proportion, accounting for 37% of the total area transferred. The ecological vulnerability of the urban green-space system shows a significant improvement trend. From 2015 to 2020, the conversion between urban and green-space ecological vulnerability levels was significantly weakened. In 2015, a total of 35,053 $km^2$ was transferred out. Although this was mainly based on slight vulnerability and mild vulnerability in 2015, it was also based on the internal circulation of slight vulnerability and mild vulnerability, accounting for 52%. In 2020, the transfer was also dominated by slight vulnerability and mild vulnerability, accounting for 35%. The ecological vulnerability of the urban green-space system still maintained an improvement trend (Tables 3 and 4).

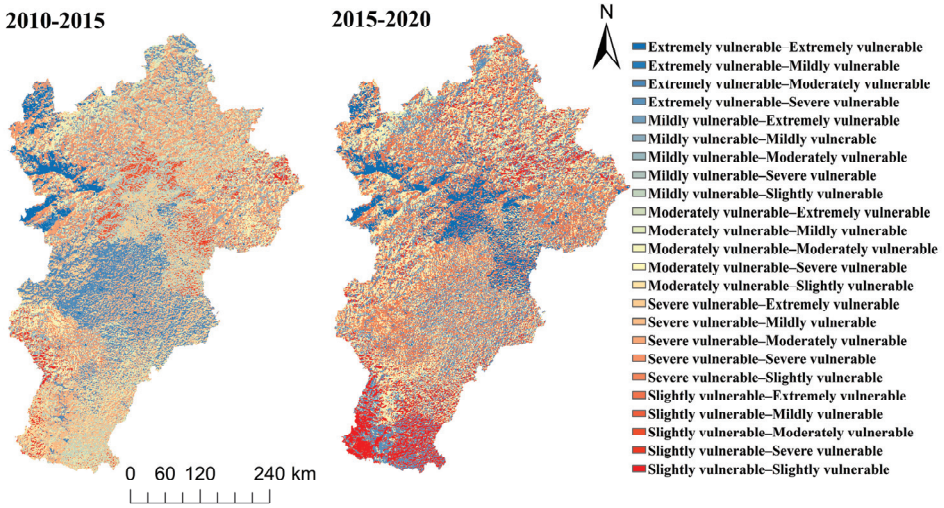



**Figure 7.** The spatial pattern changes of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020.

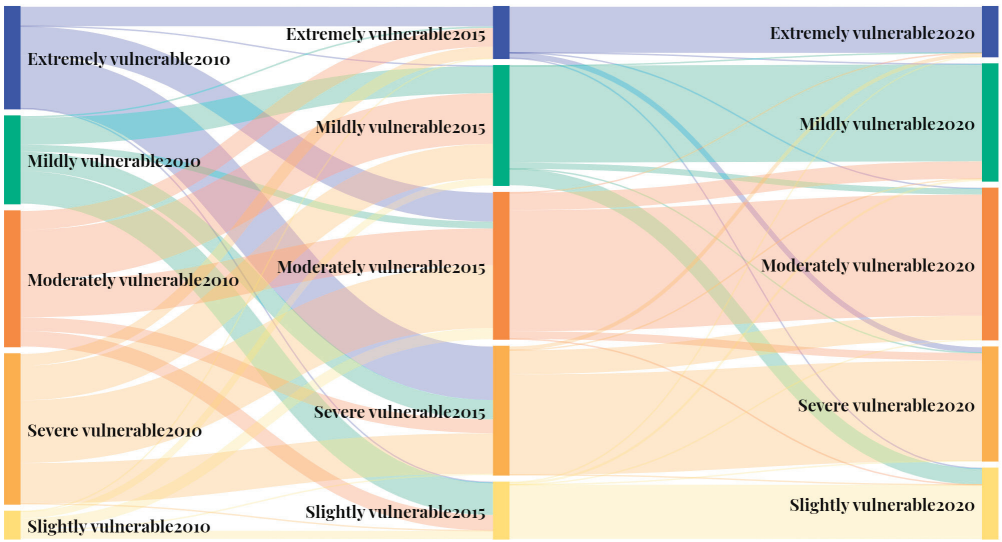



**Figure 8.** The mutual conversion area between different levels of ecological vulnerability from 2010 to 2020.

**Table 3.** The ecological vulnerability transfer matrix of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2015 ($km^2$).

| | 2010 | | | | | |
|---|---|---|---|---|---|---|
| **2015** | **Extremely Vulnerable** | **Mildly Vulnerable** | **Moderately Vulnerable** | **Severely Vulnerable** | **Slightly Vulnerable** | **Grand Total** |
| Extremely vulnerable | 8203 | 683 | 7869 | 4947 | 1 | 21,703 |
| Mildly vulnerable | 82 | 11,378 | 21,332 | 14,543 | 2897 | 50,232 |
| Moderately vulnerable | 12,119 | 2893 | 15,486 | 26,428 | 4658 | 61,584 |
| Severely vulnerable | 22,478 | 8152 | 5804 | 17,020 | 544 | 53,998 |
| Slightly vulnerable | 0 | 13,701 | 6493 | 158 | 3415 | 23,767 |
| Grand total | 42,882 | 36,807 | 56,984 | 63,096 | 11,515 | 211,284 |

**Table 4.** The ecological vulnerability transfer matrix of the urban green-space system in the Beijing–Tianjin–Hebei region from 2015 to 2020 ($km^2$).

| | 2015 | | | | | |
|---|---|---|---|---|---|---|
| **2020** | **Extremely Vulnerable** | **Mildly Vulnerable** | **Moderately Vulnerable** | **Severely Vulnerable** | **Slightly Vulnerable** | **Grand Total** |
| Extremely vulnerable | 19,382 | 0 | 2 | 1589 | 0 | 20,973 |
| Mildly vulnerable | 0 | 40,827 | 7357 | 2 | 978 | 49,164 |
| Moderately vulnerable | 0 | 2531 | 50,976 | 10,151 | 1 | 63,659 |
| Severely vulnerable | 2324 | 1 | 3244 | 42,260 | 0 | 47,829 |
| Slightly vulnerable | 0 | 6873 | 0 | 0 | 22,788 | 29,661 |
| Grand total | 21,706 | 50,232 | 61,579 | 54,002 | 23,767 | 211,286 |

#### 3.1.3. Temporal and Spatial Variation Trend of Ecological Vulnerability

In this study, the land types that changed during the two research periods were extracted. The standard deviation ellipse distribution and center-of-gravity change of the two periods were obtained using spatial statistical software tools, which were used to explain the center of gravity, spatial form, ductility, and directionality of the ecological vulnerability of the urban green-space system within the study area. From the trajectory of the center-of-gravity change, during the period from 2010 to 2015, the center of gravity of the study area gradually moved northeast. At this stage, due to the proposal of the "Beijing–Tianjin–Hebei Collaborative Development Outline" in 2014, the Beijing–Tianjin–Hebei region attached importance to the ecological environment and developed it. In particular, Hebei Province has effectively constructed the Beijing–Tianjin–Hebei ecological environment-support area. Affected by the development policy, the focus of change has gradually moved to Beijing. During the period from 2015 to 2020, the center of gravity of the study area continued to move to the northeast, but it was still within the scope of Beijing and the changes were subtle; this proved that with the continuation of ecological civilization construction and investments in environmental issues in the Beijing–Tianjin–Hebei region, the ecological vulnerability of the urban green-space system within the region gradually stabilized. In 2010, the center of gravity and severe and extreme vulnerability distribution areas fell within Hebei Province, while in 2015 and 2020, the main distribution areas of severe and extreme vulnerability distribution areas moved to Beijing and Tianjin, and the center of gravity also shifted to Beijing. It can be observed that the transfer of the center of gravity reflects the changing ecological vulnerability trend of the urban green-space system to a certain extent (Figure 9).

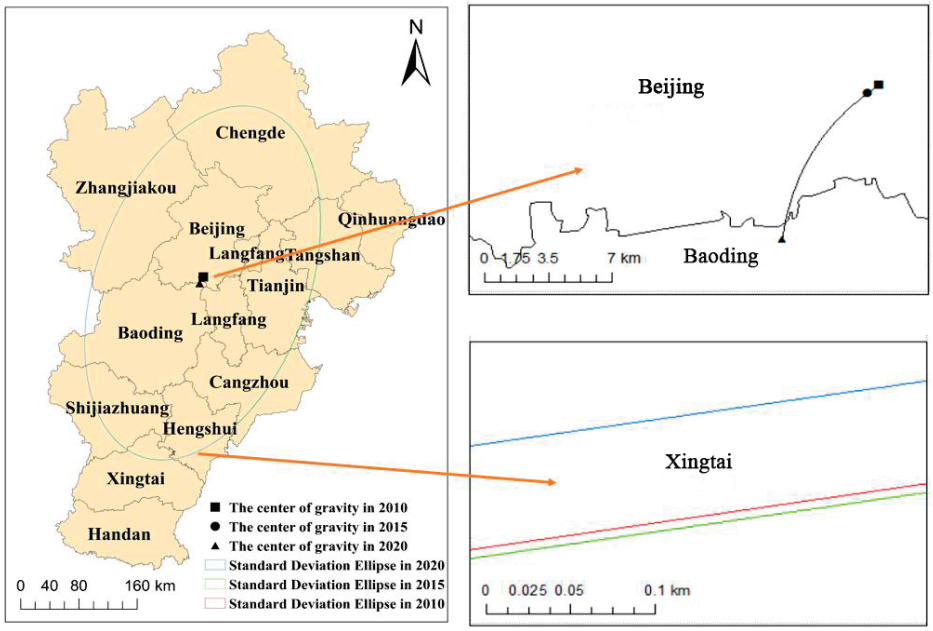



**Figure 9.** The standard deviation ellipse distribution and center-of-gravity shift of ecological vulnerability.

From the standard deviation ellipse parameters of the ecological vulnerability change of the urban green-space system, the standard deviation ellipse area increased year by year from 2010 to 2020, which proved that the ecological vulnerability change of the urban green-space system was dispersed year by year, but coverage was greater. The long axis of the standard deviation ellipse increased by 0.305 km, while the short axis decreased by 0.1221 km. According to the changes in the long and short axes, it can be observed that the ecological vulnerability-change space of the urban green-space system in the study area is slightly expanded in the east–west direction, and it was slightly contracted in the north–south direction. The azimuth of the ellipse is always around 18.7° (Table 5): that is, the direction is stable in the northeast–southwest direction. In summary, the ecological vulnerability of the urban green-space system within the study area in the past 10 years tended to increase, exhibiting an expansion trend in the main direction, and the direction is stable in the northeast–southwest direction.

**Table 5.** Standard deviation ellipse parameters of the ecological vulnerability change of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020.

| Particular Year | Ellipse Area/km$^2$ | Center Point x Coordinate | Center Point y Coordinate | Ellipse *x*-axis Length/m | Ellipse *y*-axis Length/m | Azimuth (°) |
|---|---|---|---|---|---|---|
| 2010 | 119,549.9 | 942,357.7 | 4,303,636.6 | 146.3892 | 259.9709 | 18.7 |
| 2015 | 119,551.0 | 942,357.17 | 4,303,632.17 | 146.3915 | 259.9690 | 18.7 |
| 2020 | 119,742.9 | 942,633.97 | 4,303,619.87 | 146.694.3 | 259.8488 | 18.7 |

### *3.2. Spatial Heterogeneity of the Ecological Vulnerability of the Green-Space System in the Beijing–Tianjin–Hebei Region*

#### 3.2.1. Global Spatial Agglomeration Characteristics

Global autocorrelation can describe the overall distribution of the ecological vulnerability in the study area's urban green-space system. Via the analysis and calculation of global spatial autocorrelation, the ecological vulnerability autocorrelation parameters in the study area in 2010, 2015, and 2020 were obtained. The results showed that Moran's I exhibited a continuous upward trend from 2010 to 2020. With the vigorous promotion of ecological-environment construction, the ecological-vulnerability aggregation of the urban green-space system in the Beijing–Tianjin–Hebei region gradually increased. Since the "Beijing–Tianjin–Hebei Collaborative Development Outline" was put forward in 2014,

Moran's I increased from 0.503990 in 2010 to 0.515915 in 2015. With the vigorous promotion of ecological-environment construction, Moran's I increased to 0.530715 in 2020 (Table 6), indicating that the ecological vulnerability aggregation of the urban green-space system in the Beijing–Tianjin–Hebei region has gradually increased. The ecological vulnerability of this region shows significant spatial autocorrelation, and there is positive spatial autocorrelation. That is to say that the high or low values of similar observations tended to be spatially clustered, and the grids interacted with one another. It has a very obvious agglomeration rather than a random distribution.

**Table 6.** Moran's I statistics of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020.

| Particular Year | Moran's I Index | *p* Value | Z Value |
|---|---|---|---|
| 2010 | 0.503990 | 0 | 1977.156417 |
| 2015 | 0.515915 | 0 | 2023.928773 |
| 2020 | 0.530715 | 0 | 2055.762545 |

Note: When $p < 0.05$, it is within the 95% confidence interval; when $p > 1.96$, representation data exhibit obvious aggregation characteristics. Representation data exhibit obvious aggregation characteristics.

#### 3.2.2. Local Spatial Agglomeration Characteristics

In order to analyze the distribution of the green-space system in each spatial unit in the study area, local spatial autocorrelation analyses were carried out on the distribution of the ecological vulnerability of the green-space system in the three periods. By analyzing the local spatial autocorrelation LISA agglomeration map, it can be observed that the spatial aggregation characteristics of the ecological vulnerability of the urban green-space system in the study area changed substantially from 2010 to 2015, and it showed slight differences from 2015 to 2020. Moreover, high–high aggregation and low–high aggregation areas were large and substantial, exhibiting patchy distribution and significant spatial correlation, indicating that the ecological vulnerability agglomeration characteristics of the urban green-space system were obvious, and exhibiting high–high aggregation and low–high aggregation characteristics. The low–high aggregation area was distributed on the north and south sides of the high–high aggregation area. With respect to the (1) high–high aggregation area, in 2010, it was mainly distributed in Baoding City, Langfang City, and Cangzhou City in Hebei Province, while in 2015 and 2020, it was mainly distributed in Beijing and Tianjin. With respect to (2) low and high gathering areas, in 2010, the low and high gathering areas were mainly distributed in Beijing and Tianjin, Handan City, Xingtai City, Hengshui City, and Shijiazhuang City. After 2015, the main distribution range of low and high gathering areas was transferred to Hebei Province (Figure 10).

### *3.3. Impact Factor Analysis Based on Geodetectors*

#### 3.3.1. Single-Factor Test Results

The factor detector is used to analyze the influence degree of each index on ecological vulnerability. It can be observed from the table that there are differences in the driving forces of 10 exogenous variables in the spatial differentiation of the ecological vulnerability of the urban green-space system within the Beijing–Tianjin–Hebei region. In the past ten years, annual average precipitation, education degree, and the human disturbance index q value have been relatively high and stable, and they have been maintained above 0.1. It was proven that the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region is most affected by precipitation, residents' education degree, and human disturbance. Precipitation is an exposure factor that reflects the meteorological and hydrological conditions in the study area. The human disturbance index is the expression of the disturbance degree of human activities in the urban green-space system ecosystem. The education degree of residents is the impact factor of the response dimension. When the residents' education degree is higher, they pay more attention to the construction of ecological environments, hence resulting in an urban green-space system with lower

ecological vulnerability. These three factors have a greater impact on the long-term stability of the ecological vulnerability of the urban green-space system, showing that exposure and social responses have a greater impact on the ecological vulnerability of urban green-space systems; Population density and vegetation coverage have little influence on vulnerability, and the q value is kept below 0.1. Both belong to state impact factors, reflecting that the state of the green space ecosystem itself has little impact on vulnerability (Table 7).

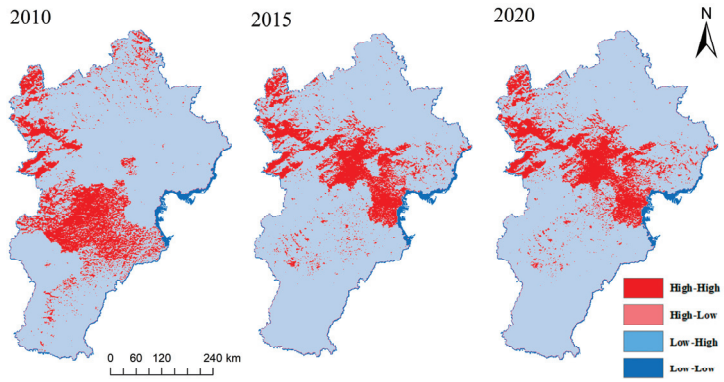
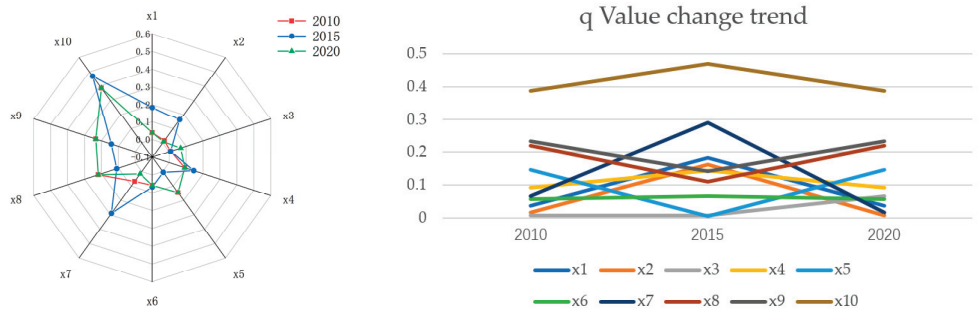



**Figure 10.** LISA agglomeration map of urban green space ecological vulnerability in the Beijing–Tianjin–Hebei region from 2010 to 2020.

**Table 7.** The statistical table of the q value and ranking of impact factors of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020.

| Impact Factors | 2010 | | 2015 | | 2020 | |
|---|---|---|---|---|---|---|
| | q | sort | q | sort | q | sort |
| Digital elevation model (x1) | 0.038 | 8 | 0.184 | 3 | 0.038 | 8 |
| GDP (x2) | 0.016 | 9 | 0.162 | 4 | 0.008 | 10 |
| Population density (x3) | 0.008 | 10 | 0.008 | 9 | 0.068 | 6 |
| Aspect (x4) | 0.092 | 5 | 0.145 | 5 | 0.092 | 5 |
| Slope (x5) | 0.146 | 4 | 0.005 | 10 | 0.146 | 4 |
| Vegetation coverage (x6) | 0.058 | 7 | 0.067 | 8 | 0.058 | 7 |
| Annual average temperature (x7) | 0.068 | 6 | 0.290 | 2 | 0.016 | 9 |
| Annual average precipitation (x8) | 0.219 | 3 | 0.110 | 7 | 0.219 | 3 |
| Human disturbance index (x9) | 0.233 | 2 | 0.142 | 6 | 0.233 | 2 |
| Education degree (x10) | 0.386 | 1 | 0.470 | 1 | 0.386 | 1 |

From 2010 to 2020, with the exception of population density and vegetation coverage, the annual average precipitation, slope, and human disturbance index exhibited a trend that first decreased and then increased, while GDP, annual average temperature, education degree, digital elevation model, and slope direction exhibited a trend that first increased and then decreased, which showed that there was a certain mutual restrictive relationship between the impact factors on ecological vulnerability (Figure 11a,b).

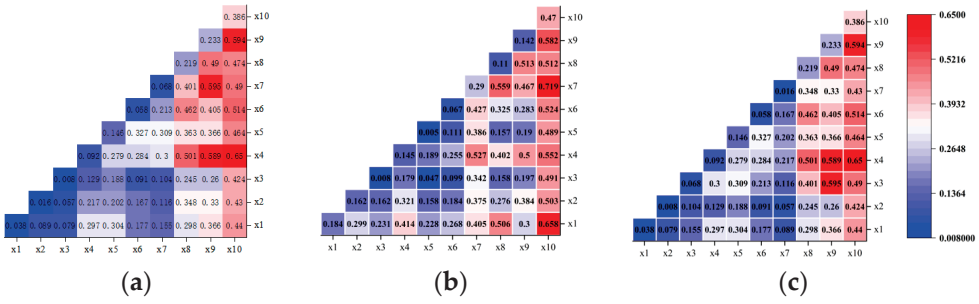



(**a**) (**b**)

**Figure 11.** (**a**) The q-value radar map of the detection results of the ecological vulnerability factors of the urban green-space system in the Beijing–Tianjin–Hebei region in 2010, 2015, and 2020 was obtained. (**b**) The trend of q value change.

### 3.3.2. Interaction Test Results

In order to study the interpretation degree of the spatial distribution of the urban green-space system's ecological vulnerability after the interaction of any two impact factors, the geographical detector was used to interactively detect each factor. The interaction detector can evaluate whether the interaction of two independent variables will increase or decrease the explanatory power of the dependent variable, which is helpful in studying the interaction between variables. From 2010 to 2020, only two types of impact factor interaction forces (nonlinear enhancement and bivariate enhancement) were observed in the Beijing–Tianjin–Hebei region. In other words, the combined effect of any two factors is greater than the effect of a single factor, which can promote the change in the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region. It can be seen from the figure that the strongest impact on the ecological vulnerability of the urban green-space system in 2010, 2015, and 2020 is the interaction between education degree and other impact factors, followed by the human disturbance index and annual average precipitation. In addition, by comparing the results of the interaction detection of impact factors from 2010 to 2020, it can be observed that when interactions between the education degree, human disturbance index, and annual average precipitation decrease, the interaction between vegetation coverage and other impact factors increases (Figure 12a–c).




(**a**) (**b**) (**c**)

**Figure 12.** The interaction effect of the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region in 2010 (**a**), 2015 (**b**), and 2020 (**c**).

To summarize, in the past ten years, the education degree, human disturbance index, and annual average precipitation in the study area have always been the dominant factors of the urban green-space system's ecological vulnerability. The influence degree of other impact factors on urban green-space system's ecological vulnerability is different. When the influence intensity of exposure factors represented by the human disturbance index and annual average precipitation decreases, the interaction intensity of the state impact factors represented by vegetation coverage will increase. It was proven that when external influences weaken, the state of the urban green-space system will determine its vulnerability.

In addition, the interaction results all comprise nonlinear and bivariate enhancements, which also show that the ecological vulnerability of the urban green-space system is a result of the combined effects of various factors.

### *3.4. Rationality Analysis of the Ecological Vulnerability Assessment Results of the Urban Green-Space System*

The remote sensing ecological index (RSEI) can reflect the ecological environment's quality in the study area [42]. The average value of the remote sensing ecological index in the study area was obtained via analyses. The average value can reflect the changing trend of the ecological environment's quality. The average values of the remote sensing ecological index in the study area from 2010 to 2020 were 0.429761, 0.459899, and 0.495763, respectively (Figure 13).

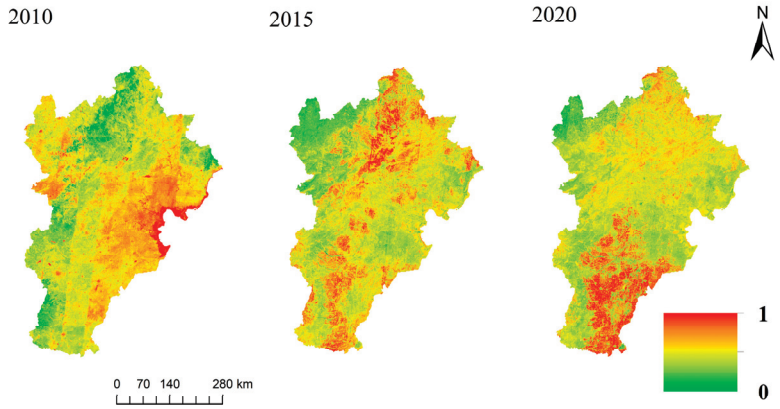



**Figure 13.** The spatial variation of remote sensing ecological index (RSEI) in the Beijing–Tianjin–Hebei region from 2010 to 2020.

The analyses of the evolution trend of the urban green-space system's ecological vulnerability can predict the development of ecological environment quality [43]. The ecological vulnerability of the study area decreased year by year, which proves that the ecological environment's quality is gradually increasing. This is consistent with the change trend reflected by the remote sensing ecological index.

In this study, the changing trend of the remote sensing ecological index and ecological vulnerability evaluation results was analyzed via a regression analysis, and a simple linear correlation between the two was obtained. The correlation coefficient $R^2$ of this study was 0.824, and the correlation significance test coefficient $R^2 = 0.824 > 0.449 = R_{0.01}$ was obtained via a regression analysis, which proves the correlation between the changing trend of the remote sensing ecological index and the ecological vulnerability index. This shows that the evaluation results of the ecological vulnerability of the Beijing–Tianjin–Hebei region are reasonable, scientific, and targeted. It can provide a reference for the planning and construction of the urban green-space system in the Beijing–Tianjin–Hebei region.

## 4. Discussion

### *4.1. The Rationality of the ESSR Urban Green-Space System's Ecological-Vulnerability Assessment*

Although many experts have carried out substantial research on ecological vulnerability in recent years, the following problems still remain: (1) there is a lack of innovation in research methods; (2) a single index is used, which renders realizing ecological vulnerability evaluation difficult; (3) the effectiveness of the evaluation results is greatly influenced by subjective factors; and (4) there is a lack of rationality analysis of the evaluation results [44]. Based on the PSR and VSD models, this study innovatively constructed the ESSR model "Exposure-Sensitivity-state-Response". The advantages of this model are as follows: (1) On the basis of retaining the original causal logic, it further broadens the dimension and clearly restores the logical relationship of "what happened, the size of the impact, the results

generated, and how to deal with it". (2) Taking into account the clear hierarchical framework, from the three levels of the goal layer, indicator layer, and factor layer, and with the help of the four categories of exposure, sensitivity, state, and response dimensions, ten impact factors were selected to comprehensively evaluate the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region. (3) The weight of factors is objectively determined, and the interference of human subjective factors is excluded. (4) On the basis of quantitative analysis and evaluation results, the ecological vulnerability of the urban green-space system is described qualitatively. In addition, this research study also uses the RSEI model to analyze the rationality of the evaluation results from the perspective of the change trend. The changing trend of the two exhibits a significant correlation, indicating that the ecological quality of the Beijing–Tianjin–Hebei region is on the rise, thus proving the rationality of the research results.

### *4.2. Discussion of the Spatial and Temporal Changes and Impact Factors of the Urban Green-Space System in the Beijing–Tianjin–Hebei Region*

In the past, research on ecological vulnerability focused on static analysis within a specific period. Although it can provide detailed information on the vulnerability of the research object in a specific period, it cannot reveal the changing ecological vulnerability trend within a long period [45]. The analysis method of the spatial and temporal changes of the ecological vulnerability of the research object is also relatively simple. For example, Zhang et al. analyzed the ecological vulnerability changes of the north karst gulf coast in Southwest Guangxi based on a simple difference method [46]. Time series analyses were used to analyze the ecological vulnerability and change trends of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020. The results show that vulnerability gradually decreased from 2010 to 2020, and the quality of the ecological environment tended to improve, which was consistent with the research results of Li et al. [47].

In the analyses of impact factors, the study observed that education level, human disturbance index, and annual average rainfall were the dominant factors in the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region in the past ten years. This result is consistent with the conclusion that human disturbance and natural factors are the main impact factors for vulnerability [48].

### *4.3. Special Features of the Research*

Different from previous research that focused on the need for urban green space for urban development, this research study begins with the ecological vulnerability of the urban green-space system itself, explores the impact of natural and human factors on the urban green-space system, and provides a scientific basis for the planning and sustainable development of urban green-space system via the analysis results.

The particularity of this research lies in its strong logic, structure, objectivity, comprehensiveness, and rationality, as well as the quantitative and qualitative analyses of the evaluation results. First of all, unlike other ecological vulnerability assessment models, the ESSR model used in this study is based on the traditional model, which provides an important foundation for subsequent research. Secondly, the study uses spatial principal component analysis to determine the weight of impact factors, which has certain objectivity. In addition, compared with other single analysis methods, the study conducted a long-term time series analysis of the ecological vulnerability of urban green-space systems, and it further conducted in-depth analyses of the evaluation results from multiple perspectives, such as spatial and temporal distributions, evolution, trends, and impact factors, providing a detailed scientific basis for the development and planning of urban green-space systems. Finally, the RSEI remote sensing ecological index was used to verify the rationality of the evaluation results.

### *4.4. Limitations and Prospects*

Although this research study has achieved many results, it still has some limitations. In terms of the selection of impact factors, although a large number of studies have been referred to and multiple impact factors have been selected as comprehensively as possible, a unified framework and measurement standard is still missing. With the further development of the city, the factors affecting the vulnerability of urban green spaces will continue to increase. In the future, the evaluation of the vulnerability of urban green-space systems should explore the utilization of a more unified model framework and select more standard impact factors.

## 5. Conclusions

In this study, using the ESSR model, ten impact factors were selected from the four dimensions of "Exposure–Sensitivity– State–Response", and the factors' weights were determined via spatial principal component analysis. With the help of GIS overlay analysis, the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region from 2010 to 2020 was evaluated, and the spatial and temporal changes were analyzed using a transfer matrix, spatial autocorrelation analysis, standard deviation ellipse analysis, and center-of-gravity migration model. The impact factors were analyzed using a geographical detector, which provides a theoretical basis for the planning and sustainable development of urban green-space systems.

The results show the following: (1) The ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region presents the distribution law of "Hebei surrounds Beijing and Tianjin", and vulnerability exhibits a downward trend. Moreover, the changing trend of the urban green-space system is closely related to the change in policy. (2) In the past ten years, the focus of change has gradually moved from Hebei Province to Beijing. Examining the main direction, the focus exhibits an expansion trend, and the direction is stable in the northeast–southwest direction. (3) The ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region exhibits very obvious clustering rather than random distributions. (4) In the past ten years, the education degree, human disturbance index, and annual average precipitation in the study area have always been the dominant factors of the ecological vulnerability of the urban green-space system. The ecological vulnerability of urban green-space systems is the result of the combined effect of various factors.

To summarize, the development of the social economy and the destruction of the natural environment resulted in exposure to substantial pressure. Under the influence of multiple factors such as its sensitivity and state, the ecological vulnerability of the urban green-space system in the Beijing–Tianjin–Hebei region is high. However, the positive response of national ecological protection policies and ecological restoration measures has resulted in a steady decline in the ecological vulnerability of the urban green-space system in the area, which has indirectly promoted the overall stability of the ecological environment. In the future, we should implement policies such as the "Beijing–Tianjin–Hebei Collaborative Development Program" and the "Beijing–Tianjin–Hebei Collaborative Development Ecological Environment Protection Plan"; recognize the ecological, economic, and strategic position of the Beijing–Tianjin–Hebei region; identify the ecological vulnerability characteristics of urban green-space systems in different regions; and realize the comprehensive improvement of the ecological environment and the sustainable development of the ecosystem in the Beijing–Tianjin–Hebei region.

**Author Contributions:** Conceptualization, X.F. and Y.L.; methodology, X.F.; software, X.F.; validation, X.F. and Y.L.; formal analysis, X.F.; investigation, X.F.; resources, X.F.; data curation, X.F.; writing—original draft preparation, X.F.; writing—review and editing, X.F. and Y.L.; visualization, X.F.; supervision, X.F. and Y.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the National Natural Science Foundation of China (Grant No. 42101393).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References


1. Ren, K.; Luo, M.Y.; Zhao, Y.H. Evaluation of ecological environment and urban development quality in Xi'an City. *Chin. J. Appl. Ecol.* **2022**, *33*, 2485–2492.
2. Adnan, A.; Anamaria, P.; Ristina, S.S. Vulnerability assessment of urban expansion and modelling green spaces to build heat waves risk resiliency in Karachi. *Int. J. Disaster Risk Reduct.* **2020**, *46*, 101468.
3. Athanasios, A.G.; Muhammad, A.; Diana, A.O. Planning small for winning big: Small urban green space distribution patterns in an expanding city. *Urban For. Urban Green.* **2022**, *78*, 127787.
4. Ingo, K. Urban wilderness: Supply, demand, and access. *Urban For. Urban Green.* **2018**, *29*, 336–347.
5. Dzifa, A.P.; Yaw, A.B. Exploring the impacts of urban expansion on green spaces availability and delivery of ecosystem services in the Accra metropolis. *Environ. Chall.* **2021**, *5*, 100283.
6. Covadonga, V.; Jordi, S.; Elena, D.C. Integrating landscape ecology in urban green infrastructure planning: A multi-scale approach for sustainable development. *Urban For. Urban Green.* **2024**, *94*, 128248.
7. Lydia, D.A.; Stephen, A.T.; Michael, O.A. The fate of urban green spaces: Assessment of the ownership, availability and conditions of parks in Accra, Ghana. *Urban For. Urban Green.* **2023**, *82*, 127897.
8. Shishir, P.; Sarah, L.S. Urban green spaces and sustainability: Exploring the ecosystem services and disservices of grassy lawns versus floral meadows. *Urban For. Urban Green.* **2023**, *84*, 127932.
9. Syrbe, R.U. The value of urban nature in terms of providing ecosystem services related to health and well-being: An empirical comparative pilot study of cities in Germany and the Czech Republic. *Land* **2021**, *10*, 341. [CrossRef]
10. Yeonsu, L.; Bokyung, S. Two-step carbon storage estimation in urban human settlements using airborne LiDAR and Sentinel-2 data based on machine learning. *Urban For. Urban Green.* **2024**, *94*, 12–23.
11. David, H.; Theodore, C.L.; Ting, M. Rocky steps towards adaptive management and adaptive governance in implementing green infrastructure at urban scale in Philadelphia. *Urban For. Urban Green.* **2020**, *55*, 126–137.
12. Long, P.F. *Study on the Green Space of Disaster Prevention and Risk Avoidance Parks in the Central Urban Area*; Beijing University of Architecture: Beijing, China, 2022.
13. Yujia, Z.; Alan, T.M.; Turner, B.L. Optimizing green space locations to reduce daytime and nighttime urban heat island effects in Phoenix, Arizona. *Landsc. Urban Plan.* **2017**, *165*, 162–171.
14. Mao, Q.Z.; Luo, S.H.; Ma, K.M. Research advances in ecological assessment of urban greenspace. *Acta Ecol. Sin.* **2012**, *32*, 5589–5600.
15. Yang, J.; Huang, X. The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. *Earth Syst. Sci. Data* **2021**, *13*, 3907–3925. [CrossRef]
16. Fareeq, T.N.; Sally, F.K.A.; Tamarah, A.A. Urban Land Use Changes: Effect of Green Urban Spaces Transformation on Urban Heat Islands in Baghdad. *Alex. Eng. J.* **2023**, *6*, 555–571.
17. Pattiyage, I.A.G.; Uthpalana, A.; Wei, D. Ecological fragmentation two years after a major landslide: Correlations between vegetation indices and geo-environmental factors. *Ecol. Eng.* **2020**, *153*, 105914.
18. Cao, E.J. *Spatiotemporal Changes of Ecological Vulnerability in Zi Wuling Area Based on the VSD Model*; Lanzhou University: Lanzhou, China, 2020.
19. Chen, F.; Li, Z.H.; Dong, S.C. Evaluation of ecological vulnerability in gully-hilly region of Loess Plateau based on VSD Model- A case of Lintao county. *Arid. Land Resour. Environ.* **2018**, *32*, 74–80.
20. Mehebub, S.; Monika, S.; Gopala, A. Assessing Wetland ecosystem health in Sundarban Biosphere Reserve using pressure-state-response model and geospatial techniques. *Remote Sens. Appl.* **2022**, *26*, 100754.
21. Huang, J.Y.; Liu, Y.; Ma, L. Review on the Theoretical Model and Assessment Framework of Foreign Vulnerability Research. *Areal Res. Dev.* **2012**, *31*, 1–5+15.
22. Xu, J.; Li, G.F.; Wang, Y.H. Review and Prospect of Research on Ecological Vulnerability in China and Abroad. *East China Econ. Manag.* **2016**, *30*, 149–162.
23. Zhang, X.R.; Zhang, Y.L.; Fang, C.L. Concept, Framework and Measurement: Review on the Research Context of Urban Vulnerability and Its Development. *Geogr. Geoinf. Sci.* **2015**, *31*, 94–99.
24. Peng, J.; Wu, J.S.; Pan, Y.J. Evaluation for Regional Ecological Sustainability Based on PSR Model: Conceptual Framework. *Prog. Geogr.* **2012**, *31*, 933–940.
25. Colin, P.; Rob, N.; Brent, Y. Building comparable global change vulnerability assessments: The vulnerability scoping diagram. *Glob. Environ. Chang.* **2007**, *17*, 472–485.
26. Dong, Y.; Fu, C.M.; Chen, N.G. Spatial differentiation of ecosystem service values in Tangshan City over the past 30 years using geographic detection. *J. Agric. Resour. Environ.* **2022**, *39*, 1196–1207.

27. Chi, Y. Spatiotemporal characteristics and ecological effects of the human interference index of the Yellow River Delta in the last 30years. *Ecol. Indic.* **2018**, *39*, 1219–1220.
28. Dai, Z.; Liu, J.T.; Xiang, Y. Human interference in the water discharge of the Changjiang (Yangtze River), China. *Hydrol. Sci. J.* **2015**, *60*, 1770–1782. [CrossRef]
29. Jia, J.J.; Zhao, J.; Wang, J.B. Ecological vulnerability assessment of Shiyang River basin based on SRP model. *J. Agric. Resour. Environ.* **2020**, *34*, 34–41.
30. Alok, R.; Laxmi, K.S. Spatial E-PSR modelling for ecological sensitivity assessment for arid rangeland resilience and management. *Ecol. Model.* **2023**, *478*, 110283.
31. Lin, M.Y.; Nan, X.X.; Hu, Z.R. Fractional Vegetation Cover Change and Its Evaluation of Ecological Security in the Typical Vulnerable Ecological Region of Northwest China: Helan Mountains in Ningxia. *J. Ecol. Rural Environ.* **2022**, *38*, 599–608.
32. Mukesh, S.; Komal, C.; Rustam, P. Eco-environmental quality assessment based on pressure-state-response framework by remote sensing and GIS. *Remote Sens. Appl.* **2021**, *23*, 100530.
33. Gong, X.S.; Han, M.L. Trends and influencing factors of ecological vulnerability in arid areas-Taking Xinjiang as an example. *Jiangsu Agric. Sci.* **2018**, *46*, 215–218.
34. Yun, F.S.; Ya, N.X.; Wen, J.C. Addressing resource scarcity and fostering sustainability through environmental education in Asia. *Resour. Policy* **2024**, *90*, 104823.
35. Xu, F.; Jiao, Y.G.; Tang, L.W. Ecological Vulnerability Evaluation and Countermeasures of Ecological Restoration in Ecological Restoration Areas of Mountains-Rivers-Forests-Farmlands-Lakes-Grasslands, Tai'an Cit. *Geoscience* **2023**, *37*, 892–902.
36. Wang, Y.F.; Bai, Q.; Sun, H. Spatial-temporal evolution and driving factors of ecological vulnerability in Fenhe River Basin from 2000–2020. *J. Zhejiang Univ. (Sci. Ed.)* **2023**, *50*, 607–618.
37. Wang, P.; Zhao, W.; Ke, X.L. Evaluation and Spatiotemporal Evolution of Ecological Vulnerability of Qianjiang Based on SRP Model. *Res. Soil Water Conserv.* **2021**, *28*, 347–354.
38. Zuo, Y.; Zhou, Y.; Li, Q. Analysis of Spatial and Temporal Changes and Trajectory Characteristics of Land Use Pattern in the Southwest Hubei. *J. Soil Water Conserv.* **2022**, *36*, 161–169.
39. Pan, Y.; Wang, Y.; Wang, Y. Spatiotemporal Dynamics of the Suitability for Ecological Livability of Green Spaces in the Central Yunnan Urban Agglomeration. *Sustainability* **2023**, *15*, 15964. [CrossRef]
40. Wang, J.F.; Xu, C.D. Geodetector: Principle and prospective. *Acta Geogr. Sin.* **2017**, *72*, 116–134.
41. Zhou, Y.; Chen, T.; Wang, J.; Xu, X. Analyzing the Factors Driving the Changes of Ecosystem Service Value in the Liangzi Lake Basin—A GeoDetector-Based Application. *Sustainability* **2023**, *15*, 15763. [CrossRef]
42. Tang, H.; Fang, J.; Xie, R. Impact of Land Cover Change on a Typical Mining Region and Its Ecological Environment Quality Evaluation Using Remote Sensing Based Ecological Index (RSEI). *Sustainability* **2022**, *14*, 12694. [CrossRef]
43. Zhou, J.; Wang, F.; Wei, W. Urban landscape and green land planning of ecologically fragile regions-A case study of Xinjiang Bole general planning. *Eng. J. Wuhan Univ.* **2005**, *6*, 105–109.
44. Zhang, X.L.; Yu, W.B.; Cai, H.S. Review of the evaluation methods of regional eco-environmental vulnerability. *Acta Ecol. Sin.* **2018**, *38*, 5970–5981.
45. Li, Y.F.; Li, C.X.; Jia, X. Spatiotemporal Changes and Causes of Ecological Vulnerability in Ulansuhai Basin. *J. Geoinf. Sci.* **2023**, *25*, 2039–2054.
46. Zhang, Z.; Hu, B.Q.; Qiu, H.H. Spatio-temporal Differentiation and Driving Mechanism of Ecological Environment Vulnerability in Southwest Guangxi Karst-North Gulf Coastal Zone. *J. Geoinf. Sci.* **2021**, *23*, 456–466.
47. Li, K.D.; Yuan, L.; Hu, X. Spatiotemporal dynamics of Production-Living-Ecological land and its impact on the environment in Beijing-Tianjin-Hebei Region. *Ecol. Sci.* **2023**, *42*, 94–102.
48. Shi, J.; Shi, P.J.; Wang, Z.Y. Effects of human disturbances on dynamic evolution of ecological vulnerability: A case study over Lanzhou-Xining urban agglomeration. *China Environ. Sci.* **2023**, *43*, 1317–1327.


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# Correlations of Spatial Form Characteristics on Wind–Thermal Environment in Hill-Neighboring Blocks

**Liang Zhao †, Yijie Zhang †, Yiting Li, Zichao Feng and Yuetao Wang ***

School of Architecture and Urban Planning, Shandong Jianzhu University, Jinan 250100, China; zhaoliang8117@sdjzu.edu.cn (L.Z.); 2021055107@stu.sdjzu.edu.cn (Y.Z.); liyiting20@sdjzu.edu.cn (Y.L.); 2021050113@stu.sdjzu.edu.cn (Z.F.)

* Correspondence: wangyuetao@sdjzu.edu.cn; Tel.: +86-130-6405-0978

† These authors contributed equally to this work.

**Abstract:** The spatial forms of hill-neighboring blocks and the wind–thermal environment are crucial components of urban planning and urban ecology. Understanding their correlation is significant for creating a healthy community and enhancing the sustainable level of buildings and their systems. Therefore, Jinan, a multi-mountainous city in China, is taken as the research area, and the ideal model of hill-neighboring blocks is built based on categories of all these block types by aerial imagery and a semantic segmentation algorithm. Then, we use the CFD simulation software PHOENICS and the evaluation system weighted by random forest to simulate and assess the wind–thermal environment. Ultimately, the correlations and specific mathematical equations between the spatial form indicators and wind–thermal environment are obtained by a parametric method. The results demonstrate that the interface density on the near-hill side and hill surface roughness are the most related indicators to the overall wind–thermal environment. The variation in block spatial form has the most distinct influence on the proportion of breeze area and PMV. The relationship determined herein can provide strategic recommendations for decision makers for optimizing the outdoor air flow of blocks and enhancing the thermal comfort of pedestrians, which helps to create a healthy and comfortable outdoor environment in multi-mountainous cities.

**Keywords:** CFD simulation; hill-neighboring block; wind–thermal environment; spatial form indicator; deep learning; random forest

**Citation:** Zhao, L.; Zhang, Y.; Li, Y.; Feng, Z.; Wang, Y. Correlations of Spatial Form Characteristics on Wind–Thermal Environment in Hill-Neighboring Blocks. *Sustainability* **2024**, *16*, 2203. https://doi.org/10.3390/su16052203

Academic Editor: Shengwei Zhu

Received: 7 January 2024
Revised: 29 February 2024
Accepted: 4 March 2024
Published: 6 March 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The world is becoming more and more urbanized, and this trend will continue for the foreseeable future; with only 2% of the world's population living in urban areas in 1800 [1], it is expected that by 2050, the world's population will reach 70% urbanization and 100% by 2092 [2]. As the country with the fastest urbanization rate in the past 30 years, China's urban areas have grown at an average annual rate of 7.9%, which is 2.14% higher than the world average. It is still likely to be the world's fastest-growing country in the future. Rapid urbanization will severely change the earth's surface. And artificial surfaces will release and absorb more heat energy than natural surfaces, significantly changing the thermal environment at the surface [3]. As essential components of the urban environment, the urban thermal environment and wind environment are closely related and are often considered simultaneously in urban design and other fields. The deterioration of the wind–thermal environment will exacerbate the urban heat island effect and air pollution and increase the energy consumption of indoor cooling and mechanical ventilation. This will lead to heat-related diseases and even death, seriously affecting human health [4].

Urban form may affect the wind–thermal environment in a variety of ways, and many scholars have concentrated on urban design and related guidance under the influence of the wind–thermal factor. The relevant research can be roughly divided into five categories:

The first is the management and control method [5,6]. Relevant policies, planning management [7,8], control modes, control indicators, and the framework of urban design [9,10] that are conducive to improving the urban wind–thermal environment are explored through the perspective of urban planning and urban design. This kind of research mainly solves macroscopic problems, and its practicability and actual improvement of the wind–thermal environment are slight now. The second is the optimization strategy, which relies on relevant numerical simulation [11], spatial analysis [12] and other methods to propose spatial optimization and update strategies for specific areas under different proposals. The matters solved by this kind of research are not highly reproducible and are limited to specific districts. The third is scheme selection, which chooses the optimal solution such as site selection and layout and urban design from the perspective of wind and thermal environments [13–16], limited to settle problems under specific districts and proposals, too. The fourth is the evaluation system, which establishes appropriate measurements for specific research objects [17,18], mostly involving the climate comfort degree [19]. And there is a low reference value for other aspects. The fifth is correlation exploration, which explores the relevance between typical urban spatial elements. Some scholars take streets as research objects to explore the impact of street spatial form on the wind environment and air quality [20–22]. Some other scholars also focus on the shape of a newly built area or the whole city, and explore the relationship between it and the wind environment from a more macro perspective [23,24]. In addition, some scholars explore the relationship between the urban thermal environment, landscape, architecture, street and other comprehensive perspectives [25–27]. This kind of research has a comparative reference value, but the indicators selected by the existing research are on an urban and architectural scale [28–30], and the factors selected on a block scale are not comprehensive and systematic enough [31,32]. The research is not deep enough, either. In addition, there is a great lack of relevant research on special landforms, such as mountain cities, basin cities, coastal cities, and so on. As a country rich in natural landform characteristics, there are a wide variety of block types, especially mountainous cities. Hills have been integrated into urban construction, and the existence of hills not only affects the texture of the city, but changes the type of surrounding microclimate, affecting the urban wind–thermal environment. In addition, the determinants of the wind–thermal environment vary at different scales, and the cost of calculation and design in actual studies is also diverse. As the basic unit of urban structure, the correlation between blocks' spatial form and the wind–thermal environment provides a reference value for enhancing the city health index. So, the specific correlation between the spatial forms and the wind–thermal environments of the urban block adjacent to the natural hill (hill-neighboring block) is worthy of further research.

As one of the typical representatives of hill-neighboring cities in northern China, Jinan has a large-scale hill in the south, which is a natural ecological barrier of the city, and a small hill scale in the downtown area, which is integrated into the city block to form a rich form of hill-neighboring block. There are 72 hills closely adjacent to urban blocks within the Jinan Ring Expressway encircled area, including Qianfo Mountain, Fohui Mountain, Jinji Mountain, Xiaogui Mountain, etc., with adequate samples. We used DJI Mavic 3 Classic UAV (unmanned aerial vehicle, DJI Innovation, Shenzhen, China) to obtain aerial images of these hill-neighboring blocks, and carried out feature extraction and identification with the help of computer vision algorithms (Figure 1). Semantic segmentation technology combined with deep learning has been applied to many aspects in the field of computer vision now, which has a good effect on image semantic segmentation [33,34]. In this research, we used the Deeplav3+ model to train the model based on a set of 1000 relevant aerial urban images, including mountains, buildings and benchmark urban scenes. Using this model, we extracted the spatial form features related to the hill-neighboring blocks. On the basis of the semantic segmentation results, this study divides these hills into three categories and seven sub-categories of prototypes (Appendix A), which are the encirclement of the hill around the block, the tangent of the hill on the block, and the embedding of the hill into the block. The enclosure of the hill around the block refers to the enclosed

relationship between the hill and the block, which can be subdivided into four types: round-shaped, L-shaped, U-shaped, and point-group shaped according to the different degree and direction of enclosure. The tangent of the hill on the block refers to the tangent relationship between the hill and the block, which can be subdivided into corner and linear on the basis of the different scale and the various tangency modes of the hill. The embedding of the hill into the block refers to the occlusal relationship between the hill and the block, which can be subdivided into a semi-embedded hill and block and a block along the hill according to the different orientation and occlusion degree of the hill. Most of the hills in the built-up area of Jinan are point-shaped hills, and the L-shaped enclosure in the hill and block enclosure is the main form of existence. This research takes this model as an example for variations in spatial form indicators and the latter wind–thermal environment numerical simulations. And it explores the correlation between the spatial form indicator and the wind–thermal environment of Jinan's hill-neighboring blocks, so as to provide a reference for the optimization of the wind–thermal environment of similar types of blocks in Jinan and other similar northern cities in China.

**Figure 1.** Example of semantic segmentation (Taking Xiaogui mountain, Muniu mountain, Ganniu mountain, Kuang mountain as examples).

## 2. Materials and Methods

### *2.1. Spatial Form of Hill-Neighboring Block*

#### 2.1.1. Selection of Spatial Form Indicators

In this research, the spatial form indicators of the hill-neighboring block are selected based on three criteria: "relating to the wind-thermal environment, characteristics of the hill-neighboring area highlighting, and CFD (Computational Fluid Dynamics) simulations valuing". The indicators can be categorized into five categories (Table 1), namely hill-block relationship, hill scale, terrain undulation degree, interface density and block structure. Among them, the hill–block relationship parameter mainly refers to the hill–block distance ($d$). The distance between the hill and block has an impact on the "narrow pipe effect" (it refers to the effect of narrow terrain on air flow. When the air flows from the open area into the canyon formed by the terrain, because the air mass cannot accumulate in large quantities, it accelerates through the canyon, and the wind speed increases. As it flows out of the canyon, the air slows down again) that may occur between the hill and the block. The junction mode of the hill–block has different effects on the wind speed, temperature, and incoming flow angle due to the orientation of the hill, the degree of enclosure of the hill around the block, and the degree of the embedding. Hill scale parameters mainly include the height ($h$), slope ($i$), and surface roughness ($Ra$). The height of the hill may affect the temperature and pressure of the valley wind. The slope may affect its wind pressure, wind speed, and incoming flow angle. The surface roughness may also affect the wind speed and pressure. For the remaining three categories, this research selects the

degree of terrain undulation ($R$), the interface density on the side of the hill ($De$) [35], and the angle between the direction of important streets and prevailing winds ($\theta$) for in-depth investigation. Among these indicators, the changing degree of terrain undulation may affect the flow of vertical winds within the block. The interface density on the hill side may affect the wind force when valley wind enters the block, which is related to the "narrow tube effect" between the hill and block. The alignment of the main streets to prevailing winds has a strong relationship with the emergence of undesirable wind fields in the block and the improvement of the wind environment.

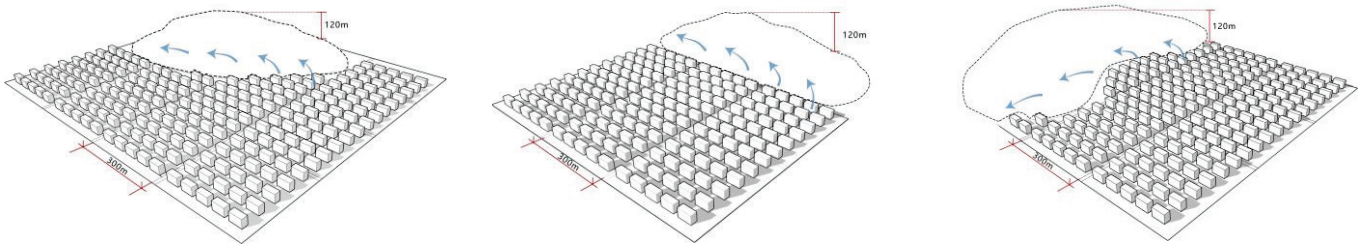
**Table 1.** Spatial form indicators of hill-neighboring block.

| Categories | Indicators | Specific Illustrations |
| --- | --- | --- |
| Relationship between hill and block | Distance between hill and block ($d$) | The distance between the building property line of the block and the green line of the hill (the control line of the no-construction zone). |
| Hill scale | Height of hill ($h$), slope of hill ($i$) | The average slope of the hill is used to refer to the slope of the hill. |
| | Surface roughness of hill ($Ra$) | |
| Terrain undulation | Degree of terrain undulation ($R$) | $R = Hmax - Hmin$ ($Hmax$ and $Hmin$ They are the maximum and minimum elevations in the block, respectively.) |
| Interface density | Interface density of near-hill side ($De$) | $De = \sum_{i=1}^{n} \frac{W_i}{L}$ (where $W_i$ represents the width of the projected surface of the building along the street in section $i$) |
| Block structure | Angel between the direction of important streets and prevailing winds ($\theta$) | |

2.1.2. Setting of Spatial Form Indicator Variations

The simulation of the outdoor wind–thermal environment generally includes two types: the real block model and the ideal block model. The real block model is suitable for discussing the merits and demerits of wind–thermal environment under different design schemes, or assessing the wind–thermal environment of specific blocks. The ideal block model is more appropriate for investigating the impact of the change in a single spatial form indicator on the wind–thermal environment around the building group. Based on this, this study chooses to establish an ideal model to explore the correlation between the spatial form indicators of the hill-neighboring block and the wind–thermal environment. The ideal model is extracted from the results of semantic segmentation, which has investigated the shapes and junction patterns of these blocks. Firstly, a benchmark model is established. Through the field investigation of the wind–thermal environment in the earlier stage, it is known that the wind–thermal environment of the block where the height of the hill is in the range of 70–180 m is positively different from that of another block of the same type. And at this time, the association between the height of the hill and the wind–thermal environment has a certain value for research. In order to facilitate the later discussion of indicator variations, the height of the benchmark model is set at 120 m. And in this research, only the hill closest to the block is considered, other surrounding hills' effect on the block is under no consideration. Referring to the formula associated with the hill terrain, the height-to-width ratio $H/L1$ (note: $H$ is the height from the top of the slope to the ground, that is, the height of the hillside. $L1$ is the horizontal distance from a point on a hillside that is half the height of the top of the slope to the top of the slope, called the length of the half slope, and $H/L1$ is the aspect ratio) is used to describe the shape and size of the hill. And it takes the height and width ratio $H/2L1$ as the average slope [36]. In addition, for the built part of the block, given that most of the block adjacent to the hill in the built-up area is a medium-height to high-height residential district, the research

follows the specific requirements of the standard for urban residential area planning and design for building height, building density, plot ratio, and minimum distance for sunlight of residential district, etc. [37]. The ideal model of the hill-neighboring block as the basic condition is set as shown in Figure 2. The block size is 300 × 300 m. The building unit size is 40 × 18 m, the building height is 27 m, the building north–south spacing is 36 m, the east–west spacing is 14 m, the building density is 0.2, the layout of building is the basic row–row type, and the building boundary is 30 m away from the plot boundary. The ideal model is used as a benchmark model for the analysis of the variables in the later stage, and in order to make the results of the study more focused, only Figure 2a has been chosen to be discussed here, and the other two types will be explored at a later stage (Figure 2).

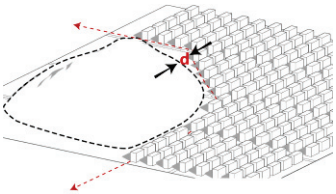
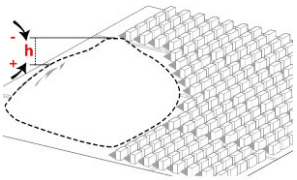
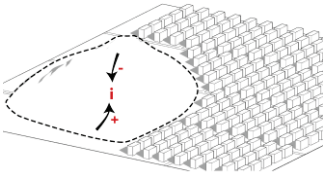
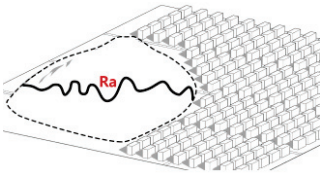
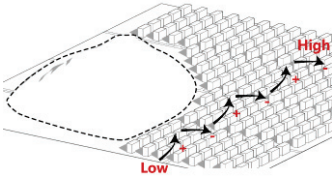
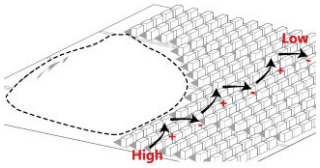
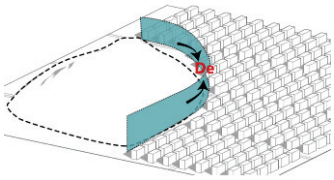
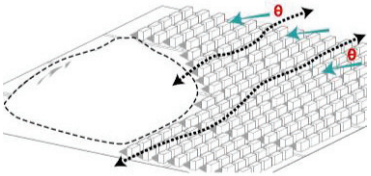



(**a**) (**b**) (**c**)

**Figure 2.** Benchmark models of three types of hill-neighboring blocks extracted from real blocks: (**a**) the encirclement; (**b**) the tangent; (**c**) the embedding.

The control variates method is adopted to set the variation of each indicator to investigate the influence of spatial form changes on the wind–thermal environment of the hill-neighboring block (Table 2); a corresponding physical model is established to reflect the variation. Indicator A series changes the spatial form of the hill-neighboring block by setting the distance between the hill and the block. Based on the benchmark model, the distance (*d*) between the hill and the block is changed, and the distance between the block and the green line of the hill is decreased and increased by 3 m, 6 m, and 9 m, respectively. Indicator B1 series sets the height of the hill (*h*) on the basis of its benchmark model by decreasing and increasing the height of the hill by 15 m, 30 m, and 45 m, separately. Indicator B2 series changes the average slope of the hill (*i*) by changing the height-to-width ratio of the hill on the basis of the benchmark model by setting the average slope to 0.3, 0.45, 0.6, 0.75, 0.9, and 1.05. Indicator B3 series changes the surface roughness (*Ra*) of the hill based on the benchmark model. They are set to 0.1, 0.15, 0.20, 0.25, 0.30, 0.35. Indicator C series sets the change in indicators by referring to the grading of the relevant slopes, limiting the slopes to those between slopes and steep slopes, i.e., 5–35°, which translates to a degree of undulation of about 8–55 m. Indicator C1 series sets the elevation of the hill side lower than that of the far hill side, and the difference in elevation is 9 m, 18 m, 27 m, 36 m, 45 m, and 54 m. Indicator C2 series sets the elevation of the hill side higher than that of the far hill side, and the difference in elevation is the same as that of C1. Indicator D series, under the premise of guaranteeing minimum distance for sunlight of buildings in block, changes the width of the projected surface of the hill side street by changing the depth of the building on the hill side, so as to change the interface density on the hill side (De). The depth of the buildings on the hill side is decreased and increased by 1 m, 2 m, and 3 m. Indicator E is based on the benchmark model, and the angle between the main street direction (east–west arrangement) and the prevailing wind direction is changed to 0°, 15°, 30°, 90°, 105°, and 120°, respectively. The settings for each working condition are shown in Table 2. The modeling software Sketchup (v2023) is suitable for multi-scale urban modeling, and can be exported or converted to a variety of formats at a later stage to be compatible with CAD (v2022), PHOENICS (v2022), and other software.

**Table 2.** Setting of variations in each spatial form indicator.

| **Indicator A series: setting of distance between hill and block variation** | **Indicator B1 series: setting of the height of hill variation** |
|---|---|
|  |  |
| Case A-1~A-6: distance reduced and increased by 3 m, 6 m, and 9 m, respectively. | Case B1-1~B1-6: height reduced and increased by 15 m, 30 m, and 45 m, respectively. |
| **Indicator B2 series: setting of the average slope of hill variation** | **Indicator B3 series: setting of the surface roughness of hill variation** |
|  |  |
| Case B2-1~B2-6: average slope is 0.20, 0.25, 0.30, 0.40, and 0.45, respectively. | Case B3-1~B3-6: surface roughness is 0.1, 0.15, 0.20, 0.25, 0.30, and 0.35, respectively. |
| **Indicator C1 series: setting of the degree of terrain undulation variation** | **Indicator C2 series: setting of the degree of terrain undulation variation** |
|  |  |
| Case C1-1~C1-6: the elevation difference between the adjacent hill and far hill is −9 m, −18 m, −27 m, −36 m, −45 m, and −54 m, respectively. | Case C2-1~C2-6: the elevation difference between the adjacent hill and far hill is 9 m, 18 m, 27 m, 36 m, 45 m, and 54 m, respectively. |
| **Indicator D series: setting of the interface density on near-hill side variation** | **Indicator E series: setting of the angle between the direction of important streets and prevailing winds variation** |
|  |  |
| Case D-1~D-6: the building depth near the hill is reduced and increased by 1 m, 2 m, and 3 m, respectively. | Case E-1~E-6: the angle between the important street direction and prevailing winds is 0°, 15°, 30°, 90°, 105°, the 120°, respectively. |

### *2.2. Wind–Thermal Environment of Hill-Neighboring Block*

#### 2.2.1. Wind–Thermal Environment Simulation

In this research, PHOENICS (v2022) is used to simulate the wind–thermal environment in the hill-neighboring blocks. It is an early commercial numerical simulation software, which has been widely used in the field of architecture design, and to simulate the wind–thermal environment at small and medium scales. It is fast and open, and the number of iterations and the simulation accuracy can be adjusted manually [38]. The simulation process is divided into three modules: pre-processing, calculation, and post-processing. The pre-processing module mainly includes the establishment of the model, the import, and the setting of boundary conditions. The calculation module is responsible for calculating the wind–thermal base value, and the process can detect the fluctuation in the residual

value. When the obtained convergence is within the error tolerance, it can be confirmed that the experiment has a reference value, and otherwise, it will return to the pre-processing module for correction. The post-processing module is for the acquisition and visualization of data, which can obtain the specific wind–thermal data of each point, and export the wind speed, wind pressure, thermal environment, and other related diagrams.

When proceeding with the wind–thermal simulation, this research sets the meteorological parameters by referencing the annual standard meteorological data of Jinan in the China Meteorological Network (The related weather dataset can be adopted at https://data.cma.cn, accessed on 10 July 2023). It includes the dominant wind direction, wind speed, wind pressure, temperature, and solar radiation in summer. And model indicators such as the roughness of the subsurface, the material of the building surface, the corresponding radiance, and the thermal conductivity of the relevant materials are set with reference to the hill-neighboring block of Jinan. The computational domain is set according to the size of the model. The appropriate turbulence model, energy model, and number of iterations are selected according to the scale of the simulated block and the required accuracy of the results. The season is set to be summer, the simulated wind speed is set to be 2.8 m/s, prevailing winds direction is east–southeast, and the solar radiation at noon is taken to be 800 W/m$^2$. The influence of the range of the wind field is limited, and it requires sufficient space to simulate the wind flow. So the computational domain is reserved to 5 times the length of the modeling area in the X-axis and Y-axis directions, and 3 times the maximum height of the model in the Z-direction. We choose the standard $k$-$\varepsilon$ equation for the turbulence model to better simulate the wind flow at the block scale. It is a two-equation turbulence model proposed by Jones et al. in 1972, which can satisfy most engineering problems and has good numerical simulation results under most wind angles [39]. And the IMMERSOL model (Formula (3)) based on the basic formula of radiation heat transfer, namely Stephan-Polz law, is used as the radiation model [40,41]. Their formulas are as follows:

$K$ equation:

$$\frac{\partial(\rho k)}{\partial t} + \nabla(\rho U k) = \nabla[(\mu + \nabla(k)] + P_G - \rho_\varepsilon \tag{1}$$

$\varepsilon$ equation:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla(\rho U \varepsilon) = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\nabla(\varepsilon)\right] + C_1\frac{\varepsilon}{k}P_G - C_2\rho\frac{\varepsilon^2}{k}\right. \tag{2}$$

$$\nabla\left\{\frac{1}{0.75 * \left(a + s + \frac{1}{L}\right)} * \nabla E_3\right\} = (a + s) * (E12 - E3) \tag{3}$$

In the formula, $u_t$ is the viscosity coefficient of turbulence, $\mu_t = C_\mu \rho \frac{K^2}{\varepsilon}$. $U$ represents the velocity vector of the fluid. $E3$ is the comprehensive emissivity, representing the net amount of radiation energy gained or lost per unit volume; $E12$ is the average radiant force on the surface of the first and binomial fluid; a is the absorption rate of the medium; $s$ is the scattering coefficient of the medium; $L$ is the distance between two solid radiating surfaces for calculation. The values of the empirical constants included in the governing equation are shown in the Table 3 below, where the first term on the left side of the equation is zero.

**Table 3.** Empirical constant of model.

| **Constant** | $C_\mu$ | $C_1$ | $C_2$ | $\sigma_T$ | $\sigma_k$ | $\sigma_\varepsilon$ |
|---|---|---|---|---|---|---|
| **Value** | 0.09 | 1.44 | 1.92 | 0.9–1.0 | 1.0 | 1.3 |

And by the numerical experiments and comparisons, it can be found that when the number of iterations is 2000, the residual value of the model will fall within the range of $1 \times 10^{-4}$~$1 \times 10^{-5}$, which can be judged to be convergent. Therefore, 2000 times are

selected as the reference iterations for the simulation. At the same time, the convergence result, the propriate boundary condition settings, and the real measured results are used to verify that the CFD simulation is reliable.

2.2.2. Selection and Assessment of Wind–Thermal Environment Indicator

The evaluation factors' selection process of the wind–thermal environment is based on the consideration of three criteria: the ease of measurement, the convenience of comparing the changes they produce, and their appropriateness to the scale of the block. Most of the evaluations related to the wind environment are focus on the mechanical effects of wind on people. The relevant indicators are instantaneous value, average value, ratio, probability, inhomogeneity factor, ventilation potential coefficient of wind speed, and proportion of breeze area, etc. These indicators focus on wind comfort and wind safety at the height of pedestrians [42]. This research selects the average wind speed, average wind speed ratio, inhomogeneity factor of wind speed, and proportion of breeze area (Table 4). Among them, the average wind speed is the mean value of the instantaneous wind speed in a given time, which is certainly representative of the wind strength. The average wind speed ratio can be used to assess the comfort of the wind environment when meteorological statistics are absent. The inhomogeneity factor of wind speed can characterize the degree of wind speed distribution in a certain region; the higher the score, the lower the inhomogeneity. The proportion of breeze area refers to the ratio of the sum of the area in the breeze zone in the study to the total area of the study area, which has a large negative impact on the suitability of walking on the street. It can be used to characterize the safety and comfort of the regional wind environment.

**Table 4.** Selected results of evaluation indicators of wind–thermal environment.

| Categories | Indicators | Specific Illustration |
| --- | --- | --- |
| Wind environment entry 2 | Average speed | The accuracy of the description of real-time wind speed is controlled according to the time interval. The larger the time interval, the rougher the description. |
| | Average speed ratio | $R = Vr/V_0$ ($Vr$ represents the average wind speed at the testing point, and $V_0$ represents the average wind speed at 10 m height of the local standard landform.) |
| | Inhomogeneity factor of wind speed | $\Delta u_i = u_i - u_N (i = 1, 2, 3, \ldots, n)$<br>$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(u_i - u_N)^2}{n-1}}$<br>Inhomogeneity factor of wind speed (horizontal) $K_u = \frac{\sigma_u}{u_N}$ |
| | Proportion of breeze area | Generally, the wind speed is 0~0.2 m/s, and the average wind speed at a height of 10 m from the ground is less than 0.2 m/s, that is, zero-level wind. |
| Thermal environment | PMV | In a steady-state thermal environment, the greater the thermal load, the farther away from the thermal comfort state.<br>$\mathrm{PMV} = [0.303\exp(-0.036M) + 0.0275]TL$ |

The evaluation related to thermal environment is a multidimensional perception process, involving the combination of physiological, physical, psychological, and behavioral factors. These include skin temperature, perspiration rate, temperature, humidity, wind speed, solar radiation, specific thermal expectations of different populations, thermal acclimatization, and thermal sensing ability, etc. [43]. There are a number of indicators that combine these factors [44,45]. The most widely used ones are predicted mean vote (PMV), physiologically equivalent temperature (PET), thermal comfort vote (TCV), thermal sensation vote (TSV), and mean radiant temperature, etc. Among them, the predicted mean vote (PMV) refers to the average value of the hot and cold sensations of most people in the same environment, which integrates the physiological and physical factors of the human body and environmental variables, and is suitable for the evaluation of the comfort of

the steady-state thermal environment. Additionally, the predicted mean vote (PMV) is an appropriate choice for block-scale thermal environment assessment.

In order to make an objective assessment of the changes in the wind–thermal environment under different circumstances, we adopt the random forest method to help build a wind–thermal evaluation system (Figure 3). The random forest is a machine learning method which includes multiple decision tree classifiers [46]. And the relative weight of each evaluation factor can be obtained when combined with the Gini index. In total, 70% of the data set is taken as training data and 30% as test data for random selection of samples. With the help of the machine learning analysis platform LIGHT Scholar (v2023), the value of mtry (max features) is adjusted according to the principle of minimum average error (Figure 4). And we use K-fold cross-validation with K = 10 to prevent overfitting. The accuracy, Kappa coefficient, and AUC values of the training set and test set are 0.760, 0.252, 0.9976, 0.753, 0.221, and 0.9875, respectively (Table 5). The results show that the model is reliable and can be used to calculate the weight of each evaluation factor (Figure 5).

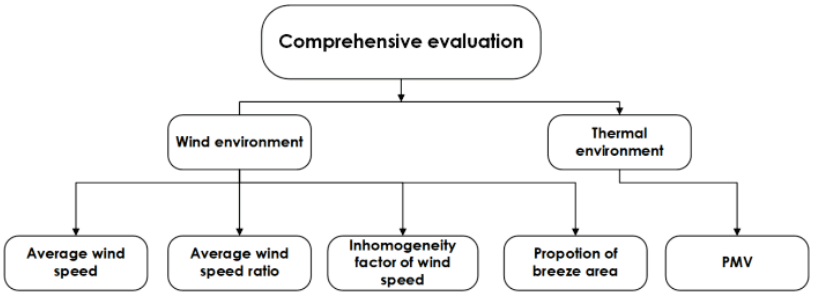
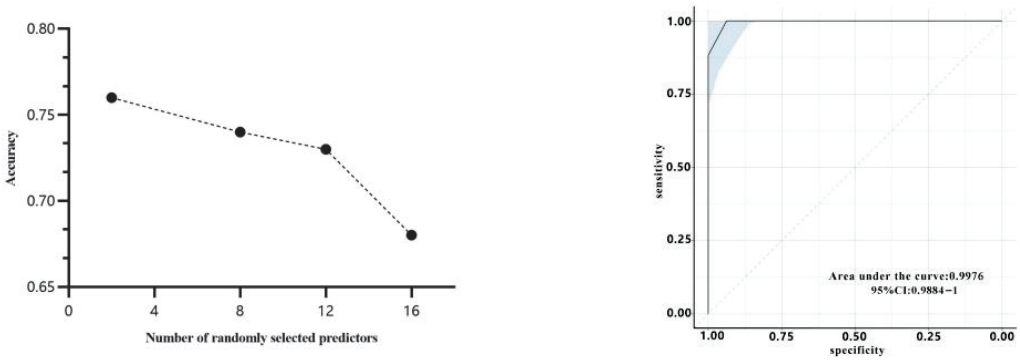



**Figure 3.** Comprehensive evaluation system of wind–thermal environment.




(**a**) (**b**)

**Figure 4.** Oob Error Distribution under different random eigenvalues and the ROC curve of random forest: (**a**) Oob Error Distribution under different random eigenvalues; (**b**) ROC curve of random forest.

**Table 5.** Performance of random forest.

| Performance Metric | Accuracy | Kappa | AUC |
|---|---|---|---|
| Training set | 0.760 | 0.252 | 0.9976 |
| Testing set | 0.753 | 0.221 | 0.9875 |

In the specific scoring of the wind–thermal simulation results for each condition, the wind–thermal numerical score of the benchmark model is defined as 0, and the other simulated conditions are compared with it, with positive scores for better than the base condition and negative scores for worse than it. The optimization degrees of 0–10%, 10–20%, 20–30%, 30–40%. . . and 90–100% correspond to 1, 2, 3, 4. . .10 points, respectively. However, considering that some spatial form indicators have prominent impacts on the wind–thermal environment and the fluctuation range is more than 100%, they take a

differential score on these metrics. For the inhomogeneity factor of wind speed (P3), when the variation is 100–150%, 150–200%, 200–250%, 250–300%. . . and 550–600%, it corresponds to 11, 12, 13, 14. . .20 points, respectively. For the proportion of breeze area (P4) indicator, 11, 12, 13, 14. . .20 points correspond to when the change is 100–120%, 120–140%, 140–160%, 160–180%, 180–200%. . . and 280–300%, respectively. For the PMV (P5), when the change is b 0–1%, 1–2%, 2–3%, 3–4%, 4–5%. . . and 9–10%, it corresponds to 1 point, 2 points, 3 points, 4 points. . . and 10 points. When the change is 10–20%, 20–30%, 30–40%. . .90–100%, and greater than 100%, it corresponds to 11 points, 12 points, 13 points, 14 points. . . and 20 points. Similarly, when the result is worse, all of the above receive negative scores (Table 6).

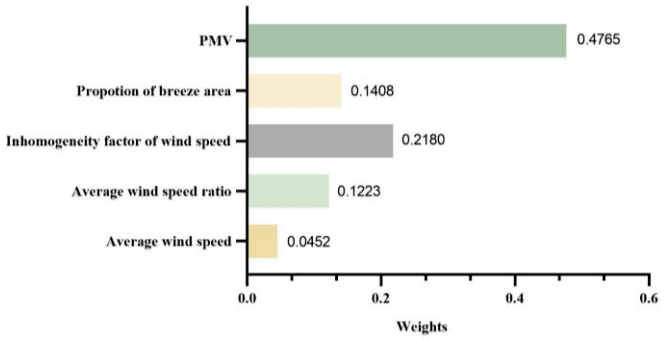



**Figure 5.** Results of weight calculation.

**Table 6.** Differential scoring reference to part of the wind–thermal environment.

| Variation / Categories | 100–150% | 150–200% | 200–250% | 250–300% | 300–350% | 350–400% | 400–450% | 450–500% | 500–550% |
|---|---|---|---|---|---|---|---|---|---|
| Inhomogeneity factor of wind speed | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| **Variation / Categories** | **100–120%** | **120–140%** | **140–160%** | **160–180%** | **180–200%** | **200–220%** | **220–240%** | **240–260%** | **260–280%** |
| Proportion of breeze area | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| **Variation / Categories** | **10–20%** | **20–30%** | **30–40%** | **40–50%** | **50–60%** | **60–70%** | **70–80%** | **80–90%** | **90–100%** |
| PMV | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |

### *2.3. Correlation Analysis*

In order to explore the correlation between the selected spatial form indicator and the wind–thermal environment and their specific laws, correlation analysis and regression analysis are chosen to analyze the relationships between the two variables. The correlation analysis adopts Pearson analysis and Spearman analysis. Pearson can determine the strength and direction of the linear relationship between the two variables, and Spearman can judge the nonlinear relationship. Employing these two methods can determine the linear and nonlinear correlation between the selected spatial form indicator and the wind–thermal environment. Regression analysis can derive mathematical formulas between two variables to help predict future trends. The coefficient of determination is used as the main index. The value of the coefficient of the determination ranges from [−1, +1]; the larger the absolute value of the coefficient, the stronger the correlation, and the higher the goodness of fit of the regression equation. If the two are linearly correlated, the coefficient is a positive number for positive correlation and a negative number for negative correlation, and if they are non-linearly correlated, they need to describe their changes with the help of specific regression equations.

This study visualizes and demonstrates the results obtained by means of correlation heatmaps and scatter plots. The correlation heat map can specifically show the linear correlation between two variables, which is the result of Pearson correlation analysis. A

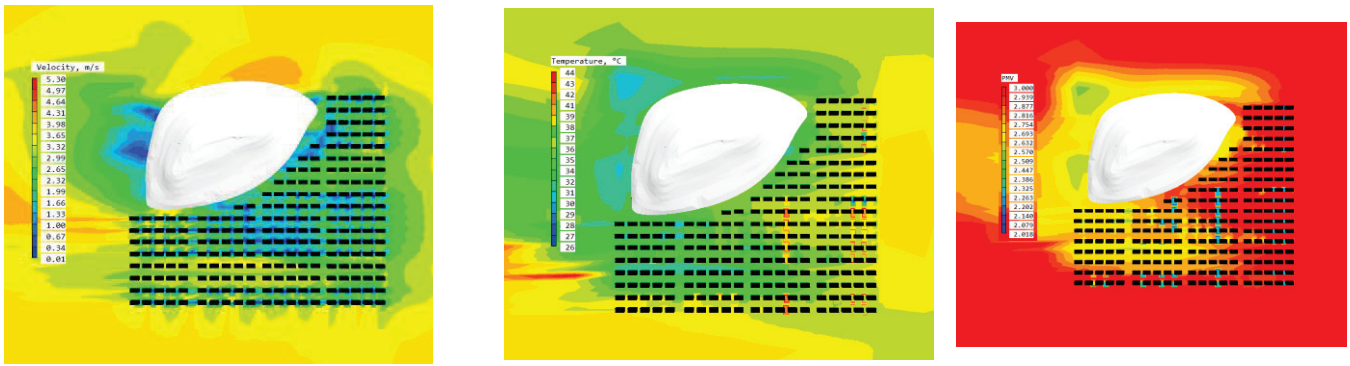
scatter plot can specifically show the linear correlation and nonlinear correlation of the variables and the regression curve, the higher the correlation, the closer the fitted curve is to the actual curve direction.

## 3. Results

### *3.1. Wind–Thermal Environment of Hill-Neighboring Block*

#### 3.1.1. Simulation of Wind–Thermal Environment

By importing the physical model corresponding to the change of each indicator into PHOENICS for simulation, the results of the wind–thermal environment under each working condition can be obtained, including wind speed cloud image, temperature cloud image, and PMV cloud image, etc., as shown in Figure 6. The color change in the figure corresponds to the change in the value. With the help of the legend on the left, the wind speed, temperature, and PMV values in the block can be more clearly and intuitively understood. In order to provide a more targeted assessment of the wind–thermal environment in the hill-neighboring block, this research does not consider the wind–thermal simulation results on the hill, and selects 12 typical testing sites in four categories inside the block, including the interface near the hill, the outermost side of the block, the typical public space surroundings, and the perimeter of the important ventilation corridors. The average value of the wind–thermal data of these 12 testing sites under each circumstance is used to represent the overall wind–thermal environment of the block (Appendix B). According to these basic wind–thermal data, the value of each indicator in the comprehensive evaluation system of the wind–thermal environment is calculated. It can be seen that the wind speed fluctuates between 1.5 m/s and 3.8 m/s, the average temperature between 33 °C and 42 °C, and the PMV value fluctuates between 2 and 2.9 under the variation of the setting of indicators A–E (Appendix B). The fluctuations of average wind speed under different indicators are different. And compared with the benchmark model, the enhancement of the average wind speed under the changes of each indicator is higher than the reduction, the average temperature shows a slight enhancement as a whole, and the PMV average value shows a reduction in general.




(**a**) (**b**) (**c**)

**Figure 6.** Visualization results of wind–thermal simulation (take CaseA-1 for example): (**a**) wind nephogram; (**b**) temperature nephogram; (**c**) PMV nephogram.

#### 3.1.2. Assessment of the Wind–Thermal Environment

The wind–thermal environment simulation results under different circumstances are graded, and the overall scores under each circumstance are compared with the single-factor scores (Figure 7). It can be seen that there is little difference in the overall scores of the wind–thermal environment for the series of cases A–E. But there are obvious contrasts among the single-factor scores of the average wind speed, the inhomogeneity factor of wind speed, and PMV. It is presumed that the selected spatial form indicators have a comparative degree of influence on the overall wind–thermal environment of the block, but there is some variability in the influence on the single factors of the wind–thermal

environment. In the comprehensive evaluation of the wind–thermal environment, the effect of hill surface roughness is more prominent, with a highest score of roughly six. The scores of average wind speed, average wind speed ratio, and PMV for each case are mostly positive numbers, and it is speculated that these spatial form indicators have a significant effect on the improvement of these wind–thermal factors. There are more negative scores of the inhomogeneity factor of wind speed and the proportion of breeze area, and it is possible that these spatial form indicators are prone to negatively affecting these two types of wind–thermal factors. The interface density on the side of the hill has the highest score under the average wind speed factor, with an average value of roughly three. The height of the hill and average slope of the hill have the highest scores under the average wind speed ratio factor, with an average value of about two. The distance between the hill and the block has the smallest negative effect on the inhomogeneity factor of wind speed, with an average value of about −1. The interface density on the side of the hill has the most positive effect on the proportion of breeze area, with an average value of about four. The hill height scores highest in the evaluation of the PMV factor, with an average value of about seven. The score can visualize and quantify the influence of spatial form indicators on the wind–thermal environment factor, but its specific correlation needs to be clarified by further correlation analysis.

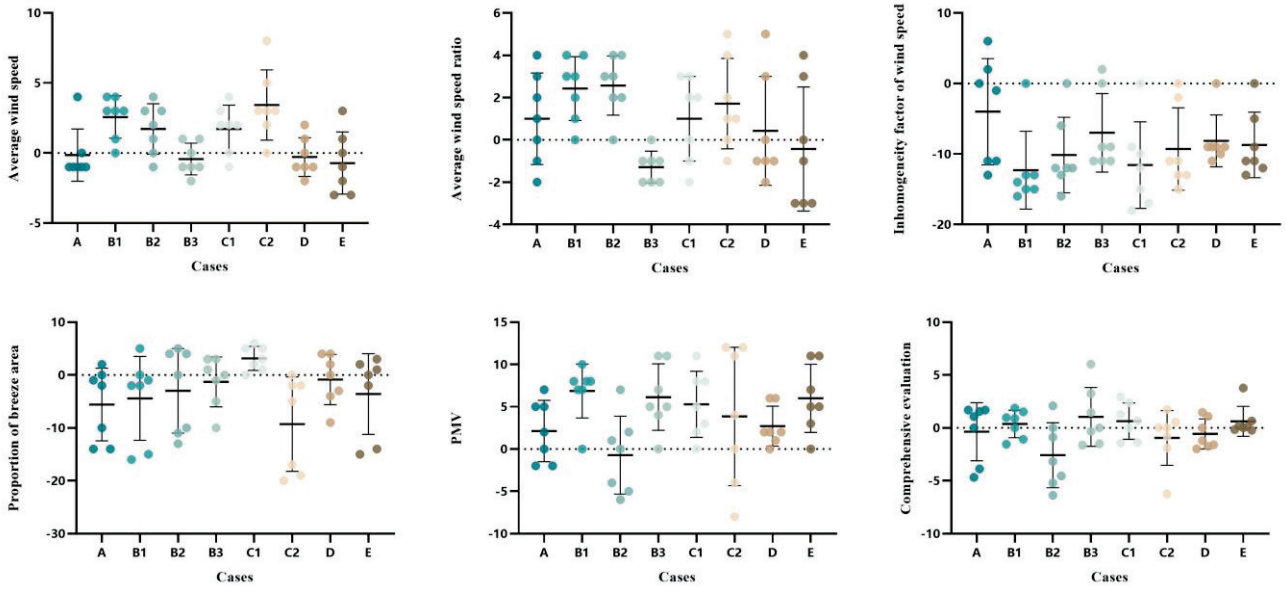



**Figure 7.** Comparison of evaluation results of each case of wind–thermal environment.

### *3.2. Association between Spatial form and Wind–Thermal Environment*

#### 3.2.1. Correlation Determination

The pairwise Pearson correlation between the hill-neighboring block's spatial form indicators and the wind–thermal environment evaluation factors is shown in Figure 8. The distance between the hill and the block and the height of the hill are strongly positively correlated with the overall wind–thermal environment; the surface roughness of the hill, and the angle between the main street direction and prevailing wind direction are obviously negatively correlated with the overall wind–thermal environment, whereas no significant correlation is found between the degree of terrain undulation of the block and the overall wind–thermal environment. In addition, the distance between the hill and block shows an obvious positive correlation with PMV. The interface density on the side of the hill shows a distinct negative correlation with the average wind speed and the inhomogeneity factor of wind speed. The height of the hill, average slope of the hill, surface roughness of the hill, and the degree of terrain undulation of the block all show clear negative correlations with the proportion of breeze area. The degree of terrain undulation of the block, the angle between the direction of the main street, and the prevailing wind direction showed

remarkable negative correlations with PMV. The correlation between two single factors of the same type is not a valuable reference, so this paper does not discuss this in detail. In addition, non-linear correlations may exist, which need to be further investigated using non-linear regression analysis.

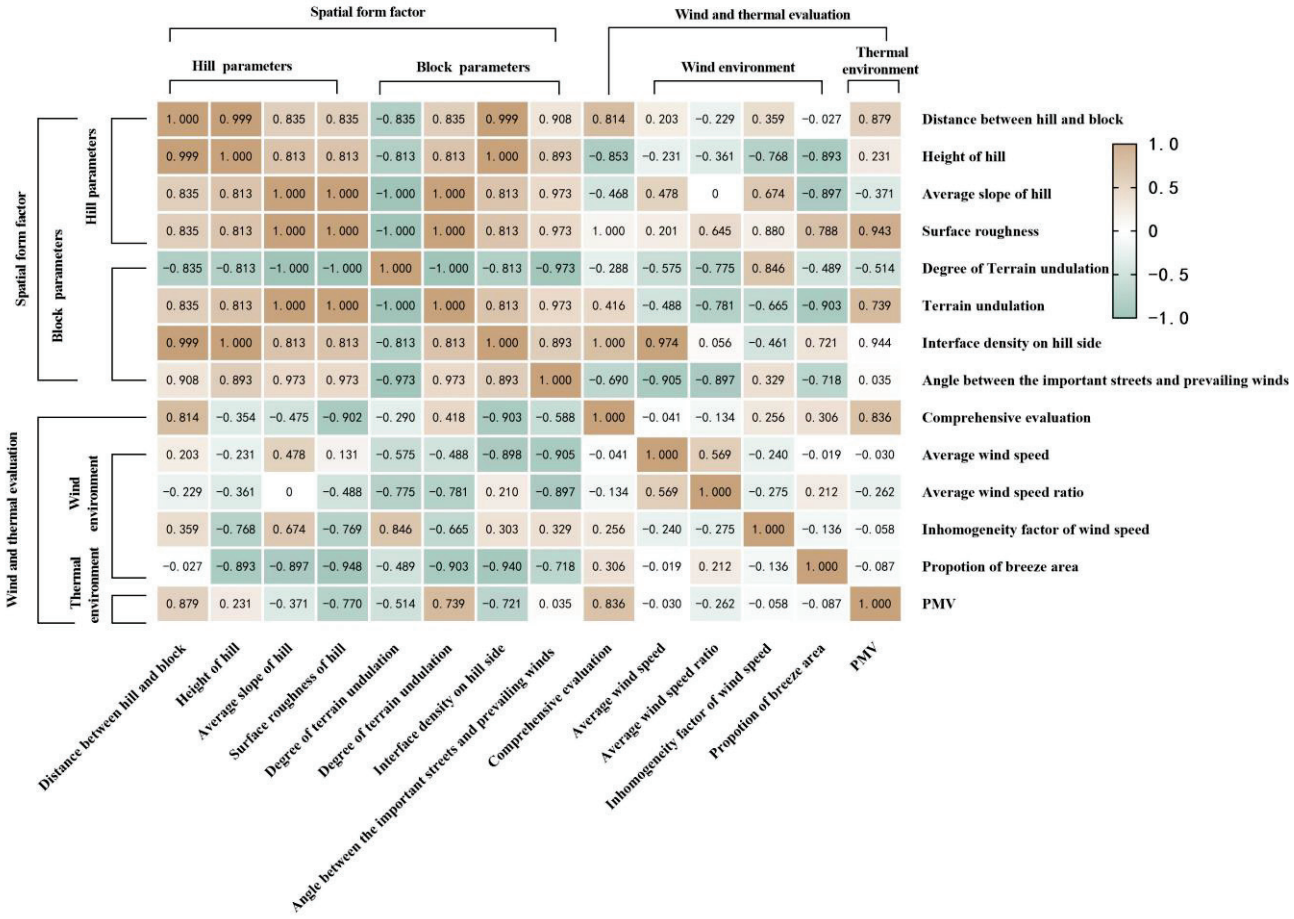



**Figure 8.** Pearson correlation statistics of spatial form indicators and wind–thermal environment factors of hill-neighboring blocks.

Through linear and nonlinear regression analyses of the relationship between the spatial form factors of the hill-neighboring block and the factors of the wind–thermal environment, the correlation results and rankings are obtained. Among the seven selected spatial form indicators, six of them, namely, the distance between the hill and block, height of the hill, average slope of the hill, surface roughness of the hill, hill-side interface density, and the angle between the main street direction and the prevailing wind direction, have clear correlations with the wind–thermal environment. And the correlation strengths of the above indicators are: hill-side interface density > surface roughness of the hill > average slope of the hill > height of the hill > angle between the main street direction and the prevailing wind direction > the distance between the hill and block (Figure 9), among which the interface density on the side of the hill is the indicator with the highest degree of fitness. Among the correlations between these seven spatial form indicators and the wind–thermal single factor, the five indicators related to the proportion of the breeze area are, in descending order of fitness: surface roughness of the hill > average slope of the hill > the degree of terrain undulation (C2) > height of the hill > degree of terrain undulation (C1). The fitting degree of the three indicators related to PMV is ranked from high to low as follows: the degree of terrain undulation (C2), the angle between the direction of the main street and the prevailing wind direction, distance between the hill and block.

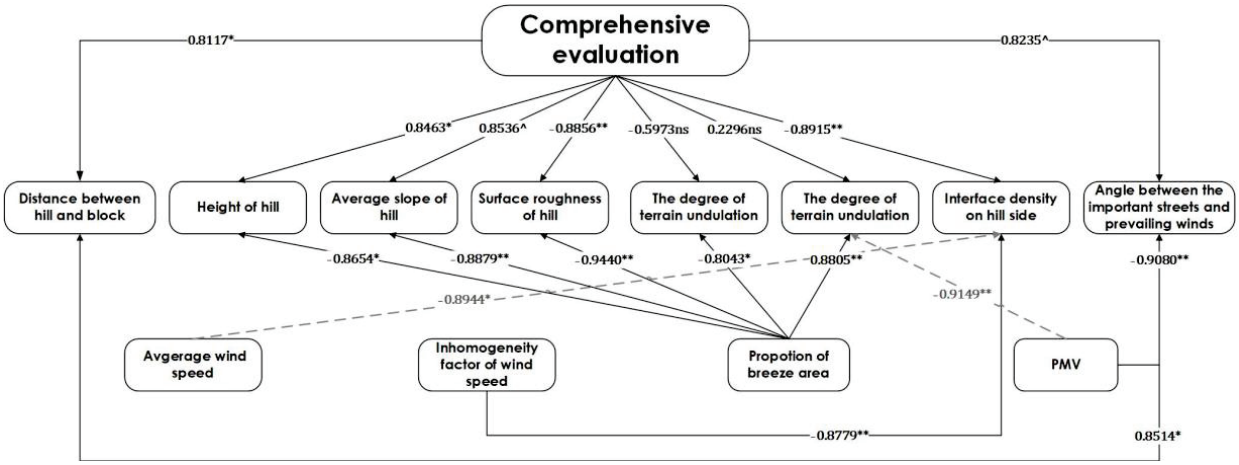



**Figure 9.** Results of correlation between spatial form factors and wind–thermal environment factors of hill-neighboring blocks (ns means that the correlation is not significant, * means that the $p$ value is <0.1, ** means that the $p$ value is <0.01, ^ means that the correlation is non-linear).

3.2.2. Specific Regression Analysis

In the correlation analysis between the spatial form of the hill-neighboring block and the overall wind–thermal environment, the interface density of the hill-neighboring side and the surface roughness of the hill have distinct linear negative correlations, with correlation coefficients of −0.8915 and −0.8856, respectively. The distance between the hill and block and the height of the hill have significant linear positive correlations, with correlation coefficients of 0.8117 and 0.8463, respectively. The average slope of the hill, the angle between the direction of important streets and the prevailing wind direction, and the overall wind–thermal environment of the hill-neighboring block are nonlinearly correlated with each other, with correlation coefficients of 0.8536 and 0.8235, respectively. The average slope of the hill, the angle between the direction of important streets and the prevailing wind direction, and the overall wind–thermal environment of the hill-neighboring block are nonlinearly correlated with each other, with correlation coefficients of 0.8587 and 0.8436, respectively. The comprehensive scores of the wind–thermal environment of the former firstly increase and then decrease, and then reach a peak when the average slope is 0.3. In the latter case, the comprehensive score of the wind–thermal environment firstly decreases and then increases, and reaches a peak at the angle of 0°. Their specific regression equations are shown in Figure 10.

In the single-factor correlation analysis, four types of indicators, namely, the height of the hill, average slope of the hill, surface roughness of the hill, and degree of terrain undulation of the block, showed apparent linear negative correlations with the proportion of breeze area, with correlation coefficients of −0.8654, −0.8879, −0.9940, −0.8043, and −0.8805, respectively. With the increase in hill height and average slope, it is easy to form more breeze areas. An increase in the roughness of the hill surface would affect the ventilation performance of the block due to the change in the roughness of the underlying surface, resulting in the formation of more breeze areas. Both types of changes in the degree of terrain undulation of the block are clearly correlated with the score of the proportion of breeze area. Such as if the trend of the terrain is low on the near side and high on the far side of the hill, the change is distinctly negatively correlated, and the score decreases as the value of the elevation difference increases. If the trend of the terrain changes to high on the near side and low on the far side of the hill, then the proportion of breeze area increases with the increment of the value of the elevation difference, and there is a significant positive correlation. It is assumed that if the terrain on the far side of the hill is high, the "narrow tube effect" may be formed within a certain range in the hill-neighboring block, which reduces the proportion of breeze area. And if the terrain on the near side of the hill is high, it will be superimposed on the effect of the original hill, which will increase

the wind shadow area of the block to a certain extent, and thus increase the proportion of breeze area. At the same time, the thermal comfort of the block is affected; in this case, the degree of terrain undulation of the block and the PMV show a significant linear negative correlation, with a correlation coefficient of −0.9149. The interface density of the hill-neighboring side with the average wind speed and the inhomogeneity factor of wind speed are both significantly linearly negatively correlated, with correlation coefficients of −0.8944 and −0.8799, respectively. The overall wind speed and the stability of the wind speed decreased with the increase in the interface density on the hill-neighboring side. The correlation between the distance between the hill and block, the angle between the important street and the prevailing wind direction, and PMV are linearly positive and negative, with correlation coefficients of 0.8514 and −0.9080, respectively, which shows that the thermal comfort of the block increases with the increment of the distance between the hill and block, and decreases with the increment of the angle between the important street and the prevailing wind direction within a certain range. The specific regression equations predicted for the wind–thermal single factor and the spatial form factor of the block are shown in Figure 11.

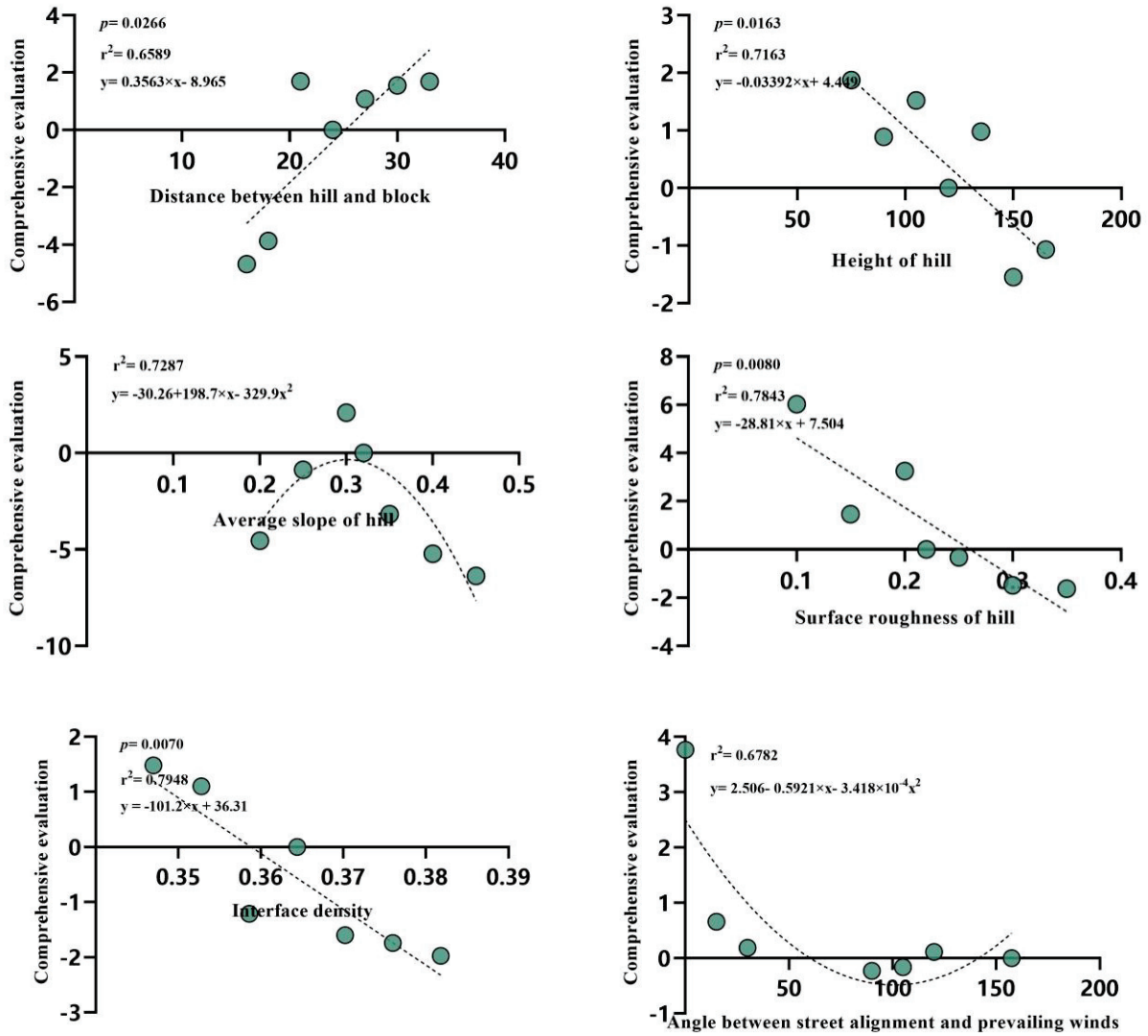



**Figure 10.** Regression analysis of spatial form and comprehensive wind–thermal environment of hill-neighboring block.

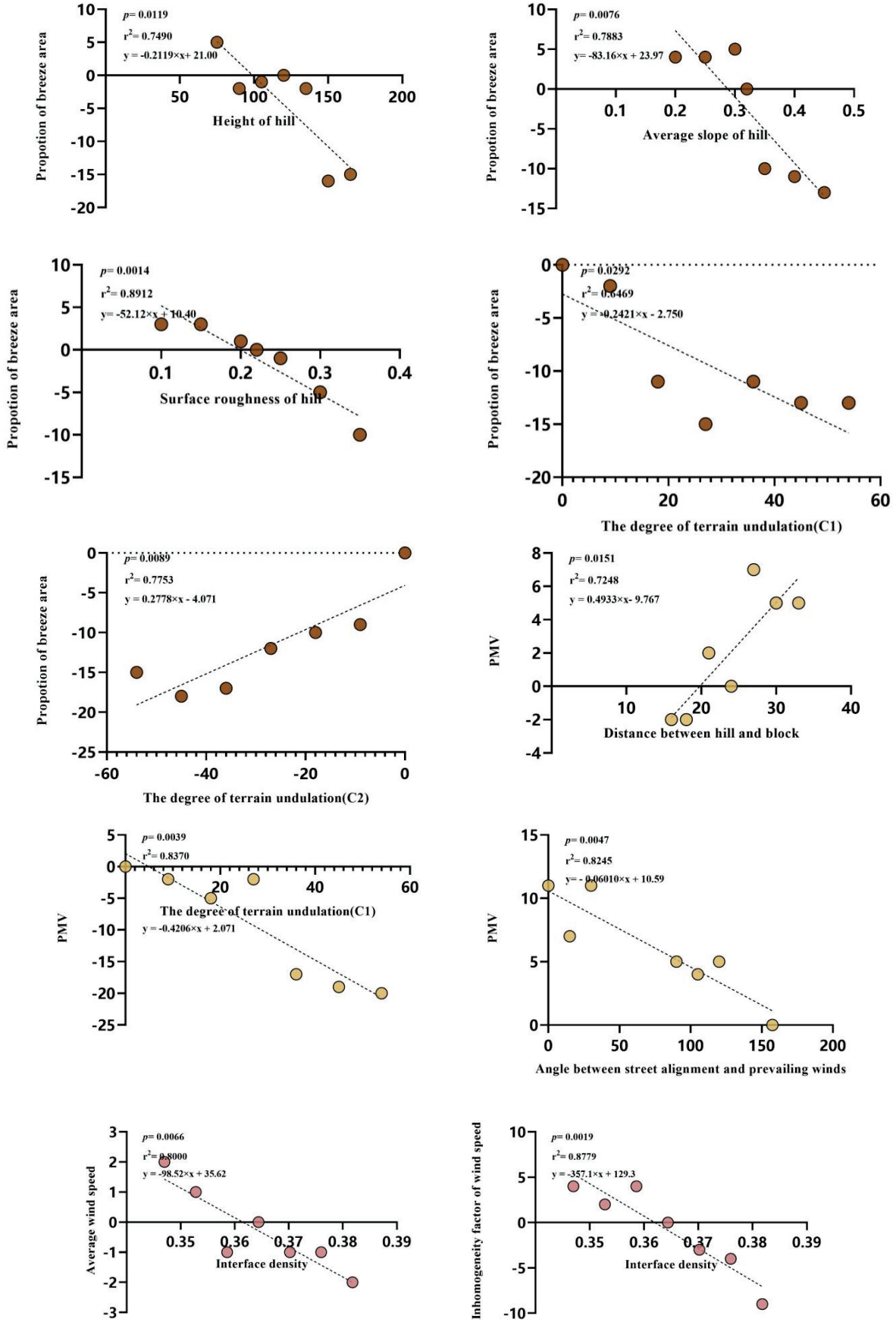



**Figure 11.** Single-factor regression analysis of spatial form and wind–thermal environment evaluation of hill-neighboring block.

## 4. Discussion

### *4.1. Application to Urban Planning and Sustainable Development*

Furthermore, as the smallest administrative unit in urban planning, blocks are conducive to urban planning departments and managers to execute relevant controls [27]. Therefore, based on our research results, suggestions for sustainable and green development of hill-neighboring blocks are put forward in the aspects of public space transformation, green plant planning and tree species matching, planning and controlling mode, building form, and layout optimization.

Firstly, among the six spatial form indicators with significant correlations with the overall wind–thermal environment, the three indicators of the height of the hill, the slope of the hill, and the surface roughness of the hill are all hill-related parameters, and it is difficult to intervene artificially with natural hills in most of the developed block, so planning should focus on how to impair the negative feedback they may generate and enhance their positive feedback. From the analysis of this research, it can be seen that they both have a distinct linear negative correlation with the score of the proportion of breeze area. Therefore, in the renewal construction of the block, the "corner space" and "enclosed space", which may become breeze area, should be intervened and transformed, so as to reduce their negative impact on the wind–thermal environment in extreme cases. In addition, heat stress in cities can be reduced, and extreme summer temperatures can be ameliorated by the planning of greenery, such as choosing vegetation with a lower density of foliage for better wind cooling [47] and planting more trees and shrubs next to buildings. The near-surface wind–thermal environment can be improved by a mixture of planting various tree species and adding vertical greening.

Then, the distance between the hill and block, the interface density of the hill-neighboring side, and the angle between the important street direction and the prevailing wind direction belong to the parameters related to the hill–block relationship and block interface and structure, and should be planned in advance under the premise of considering economic development and intensive land utilization of the undeveloped block. With reference to prevailing wind direction, the road traffic engineering arrangement, red line, and building property line in municipal construction should be set, so that the positive feedback of the indicators on the wind–thermal environment of the block can be maximized within a reasonable range. For the developed block, in order to optimize the overall wind–thermal environment of the block, the spatial form of the block near the hill should be modulated through the addition of walking green paths along the hill, micro-alteration of the building form of the block, controlling the interface density, the skyline of the hill side, and linking the street with other important ventilated spaces.

Ultimately, there is no obvious correlation between the degree of terrain undulation of the block and its overall wind–thermal environment, and the reason may be related to the hill within the block. There is already special terrain such as hills in the hill-neighboring block, and the effect of changing the degree of terrain undulation of the block on the overall wind–thermal environment is relatively negligible. However, the correlation with the wind–thermal single-factor scores of the proportion of breeze area and PMV is significant, which still has an impact on the wind–thermal environment. This correlation can be used to create local micro-terrain in the block to reduce the generation of breeze area and increase the thermal comfort of the block, thus optimizing the overall wind–thermal environment of the block and enhancing the livability of the block.

### *4.2. Limitations and Prospects*

Although the ideal benchmark model and the setting of relevant simulation parameters in this research are based on the city of Jinan, the correlation between the spatial form of the block and the wind–thermal environment as well as the specific mathematical laws obtained in this paper are still of high reference value for similar northern mountainous cities or southern cities with similar block types. And it has certain reference

significance for optimizing the spatial form of blocks and improving the level of sustainable urban development.

However, the wind–thermal environment of a block is a multidimensional perception system, which is affected by different seasons, weather, location, diurnal variation, and other factors [48,49]. Deeper research for specific objects on other aspects is needed in the future. Otherwise, there are regional differences in the attributes of blocks in different cities in China and even worldwide, which shows a lack of systematic summarization. In the future, more comprehensive and interdisciplinary [50,51] research should be established based on building climate zoning combined with regional characteristics. And the results can be applied to the spatial analysis of urban design and block regeneration, which will provide more informative support for planning strategies.

## 5. Conclusions

Based on investigation, deep learning, CFD simulation and correlation analysis, the relationship between the spatial form of hill-neighboring blocks and the wind–thermal environment has been quantitatively analyzed. The following original conclusions are drawn:

(1) Interface density on hill side and the surface roughness of the hill are the most vital indicators, with correlation coefficients of $-0.8915$ and $-0.8856$. (2) The distance between the hill and block and the height of the hill are linearly positively correlated with the overall wind–thermal environment, while interface density on the hill side and the surface roughness of the hill are linearly negatively correlated with it. The relationships between the average slope hill and the angle between the important streets and the prevailing wind and the wind–thermal environment are nonlinear, and they reach the peak value when the average slope is 0.3 and the angle is $0^{\circ}$, respectively. (3) The proportion of breeze area is the most correlated factor; height, average slope, surface roughness of the hill, and the degree of terrain undulation are all correlated with it. The second is PMV, which is correlated with the distance between the hill and block, the degree of terrain undulation, and the angle between important streets and the prevailing wind. Therefore, in the renewal construction of blocks, we should focus on those factors that may affect the proportion of breeze area. The space that may become a "breeze zone" is interfered with by a method of urban design, so that the wind can flow as much as possible inside the block. And from the perspective of green planting planning, we should reduce the negative impact of the high PMV value of the hill-neighboring block. In addition, we should optimize the spatial form of the hill-neighboring block by controlling the building density and skyline of the near-hill side, or optimize the wind–thermal environment by creating local micro-topography within the block. These findings could provide references for urban planners and decision makers to enhance the spatial form and quality of the wind–thermal environment. Meanwhile, the systematic research process of investigation, physical modeling, numerical simulation, and mathematical analysis is reproducible for exploring the correlation between the urban form of other scales and dimensions and the natural environment.

**Author Contributions:** Conceptualization, Y.Z. and Z.F.; methodology, L.Z. and Y.Z.; software, Y.Z.; formal analysis, Y.Z.; investigation, Y.Z.; resources, L.Z. and Y.L.; data curation, Y.Z.; writing—original draft preparation, L.Z. and Y.Z.; writing—review and editing, Y.W. and Y.L.; visualization, Y.Z.; supervision, L.Z., Y.W., and Z.F.; project administration, L.Z. and Y.W.; funding acquisition, L.Z. and Y.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Natural Science Foundation of Shandong Province, grant number ZR2021ME237 and The APC was funded by Natural Science Foundation of Shandong Province.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

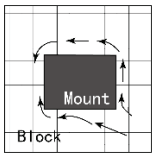
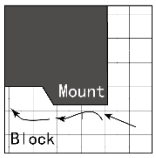
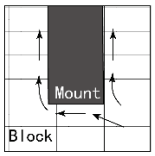
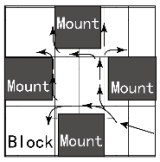
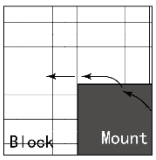
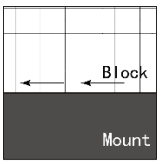
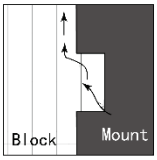
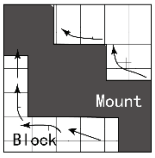
**Data Availability Statement:** The data will be provided if needed and available.

**Acknowledgments:** The authors would like to thank the anonymous reviewers for their thorough review and valuable remarks that helped to improve the manuscript.

**Conflicts of Interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A

**Table A1.** Introduction of hill-neighboring blocks prototypes.

| Categories | Sub-Categories | Spatial Characteristics | Type Schematic |
|---|---|---|---|
| The encirclement | Round-shaped | Facing the hills on all sides, the enclosure is round-shaped |   |
| | L-shaped | Facing the hills on two sides, the enclosure is L-shaped |   |
| | U-shaped | Facing the hills on three sides, the enclosure is U-shaped |   |
| | Point group | Facing more than one hill, the enclosure is point-shaped |   |
| The tangent | Corner | Tangent to the hill on both sides, which is a corner tangent |   |
| | Linear | Tangent to the hill on one side, which is a linear tangent |   |
| The embedding | Semi-embedded hill and block | The hill and the block are mortise and tenon joints. |   |
| | Block along the hill | The side near the hill is laid out along the hill shape, which is embedded with the hill. |   |

## Appendix B

**Table A2.** Simulation results of wind–thermal under different cases.

| Indicator | Case | Average Speed (m/s) | Average Temperature (°C) | Average PMV | Indicator | Case | Average Speed (m/s) | Average Temperature (°C) | Average PMV |
|---|---|---|---|---|---|---|---|---|---|
| A | A-0 | 2.18 | 38.57 | 2.78 | C1 | C1-0 | 2.18 | 38.57 | 2.78 |
| | A-1 | 2.84 | 36.76 | 2.74 | | C1-1 | 2.43 | 36.81 | 2.65 |
| | A-2 | 2.30 | 38.78 | 2.81 | | C1-2 | 1.97 | 39.34 | 2.73 |
| | A-3 | 2.27 | 40.87 | 2.82 | | C1-3 | 2.71 | 35.52 | 2.58 |
| | A-4 | 1.81 | 35.33 | 2.60 | | C1-4 | 2.58 | 37.13 | 2.42 |
| | A-5 | 2.06 | 38.59 | 2.65 | | C1-5 | 2.44 | 33.81 | 2.01 |
| | A-6 | 2.62 | 39.88 | 2.65 | | C1-6 | 2.98 | 35.82 | 2.49 |
| B1 | B1-0 | 2.18 | 38.57 | 2.78 | C2 | C2-0 | 2.18 | 38.57 | 2.78 |
| | B1-1 | 2.26 | 38.36 | 2.52 | | C2-1 | 3.10 | 42.74 | 2.86 |
| | B1-2 | 2.96 | 39.18 | 2.59 | | C2-2 | 2.64 | 36.33 | 2.67 |
| | B1-3 | 3.00 | 39.15 | 2.59 | | C2-3 | 3.81 | 40.79 | 2.97 |
| | B1-4 | 2.78 | 39.19 | 2.57 | | C2-4 | 2.72 | 33.65 | 2.08 |
| | B1-5 | 2.76 | 39.15 | 2.55 | | C2-5 | 2.65 | 35.24 | 2.49 |
| | B1-6 | 2.78 | 39.25 | 2.57 | | C2-6 | 2.52 | 35.32 | 2.08 |
| B2 | B2-0 | 2.18 | 38.57 | 2.78 | D | D-0 | 2.18 | 38.57 | 2.78 |
| | B2-1 | 2.39 | 38.89 | 2.88 | | D-1 | 1.97 | 39.85 | 2.77 |
| | B2-2 | 1.97 | 39.34 | 2.73 | | D-2 | 2.18 | 39.91 | 2.62 |
| | B2-3 | 2.70 | 38.52 | 2.58 | | D-3 | 2.42 | 41.45 | 2.61 |
| | B2-4 | 3.09 | 40.12 | 2.77 | | D-4 | 1.99 | 38.53 | 2.73 |
| | B2-5 | 3.05 | 40.36 | 2.94 | | D-5 | 1.96 | 39.66 | 2.72 |
| | B2-6 | 2.56 | 39.68 | 2.89 | | D-6 | 1.95 | 40.03 | 2.72 |
| B3 | B3-0 | 2.18 | 38.57 | 2.78 | E | E-0 | 2.18 | 38.57 | 2.78 |
| | B3-1 | 2.01 | 38.08 | 2.47 | | E-1 | 2.76 | 35.04 | 2.25 |
| | B3-2 | 1.86 | 38.79 | 2.60 | | E-2 | 2.30 | 37.89 | 2.65 |
| | B3-3 | 2.13 | 36.95 | 2.36 | | E-3 | 2.22 | 40.84 | 2.64 |
| | B3-4 | 2.12 | 37.97 | 2.64 | | E-4 | 1.54 | 34.46 | 2.58 |
| | B3-5 | 2.00 | 39.43 | 2.67 | | E-5 | 1.74 | 37.75 | 2.39 |
| | B3-6 | 2.21 | 38.58 | 2.64 | | E-6 | 1.62 | 39.53 | 2.61 |

## References


1. Wu, J. Urban ecology and sustainability: The state-of-the-science and future directions. *Landsc. Urban. Plan.* **2014**, *125*, 209–221. [CrossRef]
2. Batty, M. City 1.0, City 2.0, City n.0, . . ., City t. *Environ. Plan. B Plan. Des.* **2014**, *41*, 1–2. [CrossRef]
3. Yu, W.; Shi, J.; Fang, Y.; Xiang, A.; Li, X.; Hu, C.; Ma, M. Exploration of urbanization characteristics and their effect on the urban thermal environment in Chengdu, China. *Build. Environ.* **2022**, *219*, 109150. [CrossRef]
4. Du, S.; Zhang, X.; Jin, X.; Zhou, X.; Shi, X. A review of multi-scale modelling, assessment, and improvement methods of the urban thermal and wind environment. *Build. Environ.* **2022**, *213*, 108860. [CrossRef]
5. Liu, Y.S.; Yigitcanlar, T.; Guaralda, M.; Degirmenci, K.; Liu, A.; Kane, M. Leveraging the Opportunities of Wind for Cities through Urban Planning and Design: A PRISMA Review. *Sustainability* **2022**, *14*, 11665. [CrossRef]
6. Liu, D.; Zhou, S.; Wang, L.; Chi, Q.; Zhu, M.; Tang, W.; Zhao, X.; Xu, S.; Ye, S.; Lee, J.; et al. Research on the Planning of an Urban Ventilation Corridor Based on the Urban Underlying Surface Taking Kaifeng City as an Example. *Land* **2022**, *11*, 206. [CrossRef]
7. Pallares-Barbera, M.; Gisbert, M.; Badia, A. Grid orientation and natural ventilation in Cerdà's 1860 urban plan for Barcelona. *Plan. Perspect.* **2021**, *36*, 719–739. [CrossRef]
8. Ren, C.; Yang, R.; Cheng, C.; Xing, P.; Fang, X.; Zhang, S.; Wang, H.; Shi, Y.; Zhang, X.; Kwok, Y.T.; et al. Creating breathing cities by adopting urban ventilation assessment and wind corridor plan–The implementation in Chinese cities. *J. Wind. Eng. Ind. Aerodyn.* **2018**, *182*, 170–188. [CrossRef]
9. Palusci, O.; Monti, P.; Cecere, C.; Montazeri, H.; Blocken, B. Impact of morphological parameters on urban ventilation in compact cities: The case of the Tuscolano-Don Bosco district in Rome. *Sci. Total Environ.* **2022**, *807*, 150490. [CrossRef]
10. He, B.-J.; Ding, L.; Prasad, D. Wind-sensitive urban planning and design: Precinct ventilation performance and its potential for local warming mitigation in an open midrise gridiron precinct. *J. Build. Eng.* **2020**, *29*, 101145. [CrossRef]
11. Su, Y.; Zhao, Q.; Zhou, N. Improvement strategies for thermal comfort of a city block based on PET Simulation— A case study of Dalian, a cold-region city in China. *Energy Build.* **2022**, *261*, 111557. [CrossRef]
12. Chengrong, L.; Tian, C. Evaluation and Optimization Strategy of Cold Source Quality to Alleviate Urban Thermal Environment. *Econ. Geogr.* **2023**, *43*, 42–51. [CrossRef]
13. Peng, S.; Zou, Z.; Hong, L. Numerical simulation of wind and thermal environment in inner cities and strategies for partial renewal: A case study of dazhimen, wuhan. *City Plan. Rev* **2016**, *40*, 16–24.

14. Ma, D.; Wang, Y.; Zhou, D.; Zhu, Z.; Yang, Y. The renew plans of urban thermal environment optimization for traditional districts in Xi'an, China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 5700–5716. [CrossRef]
15. Kwok, Y.T.; Schoetter, R.; Lau, K.K.; Hidalgo, J.; Ren, C.; Pigeon, G.; Masson, V. How well does the local climate zone scheme discern the thermal environment of Toulouse (France)? An analysis using numerical simulation data. *Int. J. Climatol.* **2019**, *39*, 5292–5315. [CrossRef]
16. Peng, C.; Ming, T.; Cheng, J.; Wu, Y.; Peng, Z.-R. Modeling Thermal Comfort and Optimizing Local Renewal Strategies—A Case Study of Dazhimen Neighborhood in Wuhan City. *Sustainability* **2015**, *7*, 3109–3128. [CrossRef]
17. Liang, H.Y.; Meng, Q.L.; Li, X.H. A study of a method for evaluating the wind environment in old city renewal planning in South China: A case study of renewal planning for Yuzhu Old City, Huangpu District, Guangzhou. *South. Archit.* **2018**, *4*, 34–39. [CrossRef]
18. Gagliano, A.; Nocera, F.; Aneli, S. Computational Fluid Dynamics Analysis for Evaluating the Urban Heat Island Effects. *Energy Procedia* **2017**, *134*, 508–517. [CrossRef]
19. Wang, Z.; Liu, T. Comfort Evaluation of the Wind Environment of the Historical Sites of Haisi Culture in Quanzhou. *Chin. Landsc. Archit.* **2021**, *36*, 89. [CrossRef]
20. Miao, C.; He, X.; Gao, Z.; Chen, W.; He, B.J. Assessing the vertical synergies between outdoor thermal comfort and air quality in an urban street canyon based on field measurements. *Build. Environ.* **2023**, *227*, 109810. [CrossRef]
21. Ying, X.; Kan, Q. The Influence of Street Spatial Layout Factors on Wind Environment in Hangzhou, Zhejiang. *Sci. Geogr. Sin.* **2018**, *38*, 2093–2099. [CrossRef]
22. Bao, J.; Xu, L.; Shi, Y.; Ma, Q.; Lu, Z. The Influence of Street Morphology on Thermal Environment Based on ENVI-met Simulation: A Case Study of Hangzhou Core Area, China. *ISPRS Int. J. Geoinf.* **2023**, *12*, 303. [CrossRef]
23. Hu, T.; Yoshie, R. Indices to evaluate ventilation efficiency in newly-built urban area at pedestrian level. *J. Wind. Eng. Ind. Aerodyn.* **2013**, *112*, 39–51. [CrossRef]
24. Azizi, M.M.; Javanmardi, K. The Effects of Urban Block Forms on the Patterns of Wind and Natural Ventilation. *Procedia Eng.* **2017**, *180*, 541–549. [CrossRef]
25. Yan, S.; Zhang, T.; Wu, Y.; Lv, C.; Qi, F.; Chen, Y.; Wu, X.; Shen, Y. Cooling Effect of Trees with Different Attributes and Layouts on the Surface Heat Island of Urban Street Canyons in Summer. *Atmosphere* **2023**, *14*, 857. [CrossRef]
26. Kan, Q.; Setoguchi, T. The Correlation between Street Spatial Layout Factors and Wind Environment. In Новые Идеи Нового Века: Материалы Международной Научной Конференции *ФАД* ТОГУ; *ФГБОУ* ВО: Moscow, Russia, 2021; pp. 156–161.
27. Chen, X.; Wang, Z.; Bao, Y.; Luo, Q.; Wei, W. Combined impacts of buildings and urban remnant mountains on thermal environment in multi-mountainous city. *Sustain. Cities Soc.* **2022**, *87*, 104247. [CrossRef]
28. Li, Y.; Chen, L. Study on the influence of voids on high-rise building on the wind environment. *Build. Simul.* **2020**, *13*, 419–438. [CrossRef]
29. Ornelas, A.; Cordeiro, A.; Lameiras, J.M. Thermal Comfort Assessment in Urban Green Spaces: Contribution of Thermography to the Study of Thermal Variation between Tree Canopies and Air Temperature. *Land* **2023**, *12*, 1568. [CrossRef]
30. Ji, H.; Li, Y.; Li, J.; Ding, W. A Novel Quantitative Approach to the Spatial Configuration of Urban Streets Based on Local Wind Environment. *Land* **2023**, *12*, 2102. [CrossRef]
31. Du, Y.; Mak, C.M.; Tang, B. Effects of building height and porosity on pedestrian level wind comfort in a high-density urban built environment. *Build. Simul.* **2018**, *11*, 1215–1228. [CrossRef]
32. Lin, J.; Brown, R. Integrating Microclimate into Landscape Architecture for Outdoor Thermal Comfort: A Systematic Review. *Land* **2021**, *10*, 196. [CrossRef]
33. Ki, D.; Chen, Z.; Lee, S.; Lieu, S. A novel walkability index using google street view and deep learning. *Sustain. Cities Soc.* **2023**, *99*, 104896. [CrossRef]
34. Zuo, C.; Liang, C.; Chen, J.; Xi, R.; Zhang, J. Machine Learning-Based Urban Renovation Design for Improving Wind Environment: A Case Study in Xi'an, China. *Land* **2023**, *12*, 739. [CrossRef]
35. Zhou, Y. *Quantitative Research on Street Interface Morphology: Comparison Between Chinese and Western Cities*; Springer Nature: Berlin, Germany, 2022.
36. Zhang, J.; Liu, Z.; Xu, Y.; Ma, S.; Xu, Q. An experimental and numerical study on the charring rate of timber beams exposed to three-side fire. *Sci. China Technol. Sci.* **2012**, *55*, 3434–3444. [CrossRef]
37. China Academy of Urban Planning Design. *Standard for Urban Residential Area Planning and Design*; Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2018.
38. Buccolieri, R.; Santiago, J.L.; Martilli, A. CFD modelling: The most useful tool for developing mesoscale urban canopy parameterizations. *Build. Simul.* **2021**, *14*, 407–419. [CrossRef]
39. Chen, P. Numerical Study of Terrain Influence on the Airflow over Hilly Land. Master's Thesis, Zhejiang University, Hangzhou, China, 2007. Available online: https://kns-cnki-net-443.webvpn.sdjzu.edu.cn/kcms2/article/abstract?v=9w9hjx65dQT4xmTsQZioCM0dIr2GsZQPMa8QTM0v7XLz0MWTRnGRu4zgXvZMWXS4wXS3HUinxgt46NUY4XrCEZZ6tyYGrQHauA1Pj5o7qqq0NvITnZ_z3gHHsjMcC89qDa_UPxSiiM9fa7rwh4HDw==&uniplatform=NZKPT&language=CHS (accessed on 6 July 2023).
40. Markatos, N.C. The mathematical modelling of turbulent flows. *Appl. Math. Model.* **1986**, *10*, 190–220. [CrossRef]
41. Rodi, W. *Turbulence Models and Their Application in Hydraulics*; Routledge: London, UK, 2017. [CrossRef]

42. Du, Y.; Mak, C.M. Improving pedestrian level low wind velocity environment in high-density cities: A general framework and case study. *Sustain. Cities Soc.* **2018**, *42*, 314–324. [CrossRef]
43. Coccolo, S.; Kämpf, J.; Scartezzini, J.L.; Pearlmutter, D. Outdoor human comfort and thermal stress: A comprehensive review on models and standards. *Urban. Clim.* **2016**, *18*, 33–57. [CrossRef]
44. Rupp, R.F.; Vásquez, N.G.; Lamberts, R. A review of human thermal comfort in the built environment. *Energy Build.* **2015**, *105*, 178–205. [CrossRef]
45. Zhu, Y. How to create a healthy and comfortable indoor thermal environment: Exploration on the relationship between the built environment and human comfort and health. *World Archit.* **2021**, *3*, 42–45.
46. Ma, X.; Zhang, J.; Wang, P.; Zhou, L.; Sun, Y. Estimating the nonlinear response of landscape patterns to ecological resilience using a random forest algorithm: Evidence from the Yangtze River Delta. *Ecol. Indic.* **2023**, *153*, 110409. [CrossRef]
47. Salata, F.; Golasi, I.; Vollaro, A.D.L.; Vollaro, R.D.L. How high albedo and traditional buildings' materials and vegetation affect the quality of urban microclimate. A case study. *Energy Build.* **2015**, *99*, 32–49. [CrossRef]
48. Moffett, K.B.; Makido, Y.; Shandas, V. Urban-Rural Surface Temperature Deviation and Intra-Urban Variations Contained by an Urban Growth Boundary. *Remote Sens.* **2019**, *11*, 2683. [CrossRef]
49. Santamouris, M. Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. *Sci. Total Environ.* **2015**, *512–513*, 582–598. [CrossRef]
50. Mortezazadeh, M.; Zou, J.; Hosseini, M.; Yang, S.; Wang, L. Estimating Urban Wind Speeds and Wind Power Potentials Based on Machine Learning with City Fast Fluid Dynamics Training Data. *Atmosphere* **2022**, *13*, 214. [CrossRef]
51. Yao, Y.; Chang, C.; Ndayisaba, F.; Wang, S. A New Approach for Surface Urban Heat Island Monitoring Based on Machine Learning Algorithm and Spatiotemporal Fusion Model. *IEEE Access* **2020**, *8*, 164268–164281. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# Differential Analysis of Island Mountain Plant Community Characteristics: Ecological Sensitivity Perspectives

**Jinyan Liu [1,2,†], Junyi Li [1,†], Daoyuan Chen [1], Linye Guo [1], Guochang Ding [1,*] and Jianwen Dong [1,*]**

[1] College of Landscape Architecture and Art, Fujian Agriculture and Forestry University, 63 Xiyuangong Rd., Fuzhou 350002, China; fjljy@qztc.edu.cn (J.L.); 22319075007@fafu.edu.cn (J.L.); 12319075054@fafu.edu.cn (D.C.); 12319075047@fafu.edu.cn (L.G.)

[2] College of Resource and Environmental Sciences, Quanzhou Normal University, 398 Donghai Rd., Quanzhou 362000, China

* Correspondence: fjdgc@fafu.edu.cn (G.D.); fjdjw@fafu.edu.cn (J.D.); Tel.: +86-132-3590-5585 (G.D.); +86-136-0952-5156 (J.D.)

† These authors contributed equally to this work.

**Abstract:** Island plants form the foundation for maintaining the ecology of an island. With the development of the island's infrastructure, its ecosystems become damaged to a certain extent. A comprehensive understanding of island habitats and plant community characteristics is crucial for the development of island plant communities. This paper focuses on Pingtan Island in Fujian Province, China, as the research subject. Firstly, considering the significance of the wind environment on the island, this study constructed a wind environment model for the entire island of Pingtan to evaluate the ecological sensitivity from a macro perspective. Subsequently, 33 typical sample plots were selected based on different ecologically sensitive areas to conduct a micro-survey and the characterization of the montane plant communities on Pingtan Island. The findings reveal that (1) Pingtan Island's ecological sensitivity is dominated by areas with ecological insensitivity (35.72%), moderate ecological sensitivity (33.99%), and high ecological sensitivity (18.02%). The soil texture, wind environment, and land use type are the primary influencing factors in the ecological sensitivity of Pingtan Island. (2) A total of 47 families, 82 genera, and 93 species of plants were investigated in a typical sample site in the mountainous area of Pingtan Island. The plant community structure was dominated by the successional stage of shrubs and herbs. There is some similarity in the plant composition of different ecologically sensitive areas. High ecologically sensitive areas have more species. As sensitivity increases, the dominant species in the three ecologically sensitive areas continue to undergo plant succession from *Acacia confusa* to *Pinus thunbergii* to *Eurya emarginata*. (3) Both community characteristics and species diversity vary between sensitive areas. The canopy density (CD) and the mean height of tree layer (MHTL) are higher in moderate ecologically sensitive areas. The mean tree diameter at breast height (MDBH) and the mean height of shrub layer (MHSL) are higher in high ecologically sensitive areas, while the mean height of herb layer (MHHL) is higher in extreme ecologically sensitive areas. Four diversity indicators increase with increasing sensitivity. In the moderate and high ecologically sensitive areas, *Casuarina equisetifolia* and *A. confusa* thrive, with *Pinus thunbergii* showing the opposite trend. However, species diversity is better characterized by *A. confusa* and *P. thunbergii*, with *C. equisetifolia* being the least diverse. Both the community characteristics and species diversity of *P. thunbergii* are optimal in extreme ecologically sensitive areas. In this study, the ecological sensitivity of Pingtan Island and the characteristics of montane plant communities were systematically analyzed to explore more stable montane plant communities on the island, aiming to provide a scientific basis and model reference for the ecological restoration and sustainable development of Pingtan Island and other islands.

**Keywords:** Pingtan Island; wind environment simulation; plant community composition; species diversity

**Citation:** Liu, J.; Li, J.; Chen, D.; Guo, L.; Ding, G.; Dong, J. Differential Analysis of Island Mountain Plant Community Characteristics: Ecological Sensitivity Perspectives. *Sustainability* **2024**, *16*, 1988. https://doi.org/10.3390/su16051988

Academic Editor: Irene Petrosillo

Received: 11 December 2023
Revised: 31 January 2024
Accepted: 20 February 2024
Published: 28 February 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

With the rapid advancement of the globalized economy, nations worldwide have prioritized marine development as a key strategic objective. Serving as the forefront in marine economic development [1], islands possess immeasurable political, economic, military, scientific research, and ecological significance. Nevertheless, islands, being quintessential fragile ecosystems, commonly grapple with ecological and environmental challenges, such as the scarcity of freshwater resources, infertile soil, and limited biodiversity [2,3]. The 908 specialized studies focused on island coastal zones completed post-2011 reveal that global warming, the surge in extreme weather events, and prolonged, unregulated, and crude large-scale development have induced alterations in island topography and geomorphology, thereby exacerbating the degradation of island ecosystems [3]. In contrast to mainland areas, island ecosystems face formidable challenges in recovering once disturbed or damaged and may even undergo irreversible and accelerated deterioration [4]. Consequently, the protection of islands has evolved into a global ecological imperative that demands unwavering attention. Presently, within the framework of addressing challenges related to biodiversity conservation and ecological security, China is dedicating significant efforts to the protection, restoration, and sustainable tourism of its islands.

Ecological sensitivity pertains to the degree of responsiveness of ecosystems to internal and external pressures, such as changes in the natural environment and disturbances from human activities, within a given region [5]. Conducting ecological sensitivity assessments to identify potential ecological challenges can furnish essential foundational information for addressing environmental issues. The construction of a suitable evaluation system, tailored to the characteristics of the study area, stands as a particularly pivotal aspect of an ecological sensitivity assessment. In the extant literature, factors such as elevation, soil composition, water quality, and vegetation coverage are commonly considered in ecological sensitivity evaluations [5–7]. It is noteworthy that the habitat characteristics of sea islands, owing to their unique geographical locations, can be significantly influenced by the wind environment. Strong winds, for instance, may carry a substantial amount of sand, accelerating soil erosion and rendering many plants unable to thrive or grow optimally. This, in turn, results in the progressive deterioration of environmental quality. However, the incorporation of this evaluation metric is not widespread in current research [8]. This is due to the complexity of the island wind environment, which is both seasonal and stochastic, posing challenges in obtaining accurate research data. Commonly employed methods for data collection in wind environment studies encompass field tests, wind tunnel tests, and numerical simulation methods [9–11]. In comparison, numerical simulation is favored for its efficiency in terms of time and cost savings. Computational Fluid Dynamics (CFD) simulation, as a common method in numerical simulation, is widely used at the micro- and mesoscales for simulating wind environments, such as building monoliths and communities [12,13]. The method is considered to be able to better handle complex urban downgradient surfaces, allowing a refined representation of the internal wind field of the modeled object, and has proved to be reliable and superior. However, due to the high dependence on computer resources, research applications of CFD simulations at larger scales are still relatively rare at present. Based on this, this paper proposes to introduce the CFD simulation method to establish the wind environment model of Pingtan Island to determine the construction method of a large-scale wind environment model and the selection of suitable simulation software. Wind environment data were extracted as a crucial indicator for ecological sensitivity evaluation, and the evaluation system was refined to provide more detailed data support for the habitat assessment of Pingtan Island.

The island's montane plants, as the island's most important green patches, form the skeleton of the island's main ecological patches. Typical plants in the mountainous areas of the island are usually common and suitable plants or zonal plants of mountainous areas. After a long period of reproduction, renewal, and succession, they became the dominant species with certain ecological niches, wider distributions, and more quantitative characteristics on the island. At present, plant restoration through artificial forest planting

and ecological protection policy management and other human-regulated methods has become a common ecological restoration method for islands. However, due to the specificity and sensitivity of the environment, there are few species of plants suitable for growing in the island mountains; the biodiversity is extremely low, and there is often poor growth, which varies from one sensitive area to another. On the other hand, due to the lack of sufficient basic information and technical means, a plant used for ecological restoration on islands is often eliminated because it is not adapted to the environment [14]. Based on this, do the differences among the different ecologically sensitive areas of the islands lead to different characteristics of their montane plant communities? What are the characteristics of relatively stable montane plant communities in different ecologically sensitive areas? This will help to enrich the basic information on mountain plants on the islands and will be of great significance in guiding the targeted protection of island ecosystems and the promotion of plant restoration.

Pingtan Island, the largest island in Fujian Province, China, serves as a crucial ecological barrier along the southeast coast of the country. Positioned as a significant gateway for exchanges between mainland China and Taiwan Province, Pingtan Island holds strategic importance for the nation's economy and ecology. Recognized as a typical ecologically fragile island region [15], Pingtan Island is confronted with increasingly prominent ecological security challenges amidst rapid urbanization, mirroring the issues faced by other islands [16] Moreover, being one of the high-wind regions in the country [17], Pingtan Island is consistently impacted by wind and sand throughout the year. Previous studies have indicated that, in Pingtan, the closer one is to the coastline and the higher the elevation, the greater the wind speed, resulting in diminished ecological stability and a deteriorating environment [18]. This circumstance further exacerbates reforestation efforts, posing exceptional challenges [19]. It is well known that plants play an important role in regulating and improving ecological environment management, such as windbreak and sand fixation. As the important green ecological skeleton of Pingtan Island, mountain plants are very important to the ecological environment of Pingtan Island. Pingtan Island belongs to the subtropical evergreen broad-leaved forest vegetation zone. The primary vegetation has been mostly destroyed and is now dominated by secondary vegetation, supplemented by artificial protection forests. The main dominant species include *Pinus thunbergii*, *Acacia confusa*, and *Casuarina equisetifolia* [20]. Ecological succession generally progresses through four successional stages: scrub, coniferous forest, coniferous and broad-leaved mixed forest, and evergreen broad-leaved forest [21]. In 2009, following a change in administrative divisions to establish an independent administrative status, Pingtan Island underwent significant landscape renovations. These alterations, whether intentional or unintentional, introduced exotic plants and potentially heightened the island's ecological vulnerability [15,22,23]. Pingtan Island encompasses a botanical diversity comprising 541 species representing 127 families and 369 genera of seed plants. Among these, 330 species are indigenous, including exemplars of typical island native flora, such as *Eurya emarginata* and *Ipomoea pes-caprae*. Additionally, there are 211 exotic plant species, with some naturalized plants, including *Oenothera drummondii*, *Ipomoea cairica*, *Pinus thunbergii*, *Casuarina equisetifolia*, *Acacia auriculiformis*, and *Acacia confusa* [20]. Given these considerations, selecting Pingtan Island as the focal point for this study becomes both typical and imperative. This study aims to conduct an evaluation of the island's ecological sensitivity and to investigate and characterize mountain plants. The objectives of this work include the following:

(1) Conduct a comprehensive evaluation of the ecological sensitivity of Pingtan Island as a whole, with a systematic assessment of its ecological sensitivity characteristics;

(2) Undertake a survey of plant resources in the mountains of Pingtan Island to identify the composition of species and dominant species in different ecologically sensitive areas. Additionally, the study aims to explore the characteristics and species diversity of plant communities across various ecologically sensitive areas.

This study aims to identify a relatively stable model for plant communities in the mountainous region of Pingtan Island. The findings hold significant implications for the

ecological restoration and landscape optimization of Pingtan Island. Furthermore, this study serves as a valuable reference for landscape construction on other islands. The flowchart of the study is shown in Figure 1.

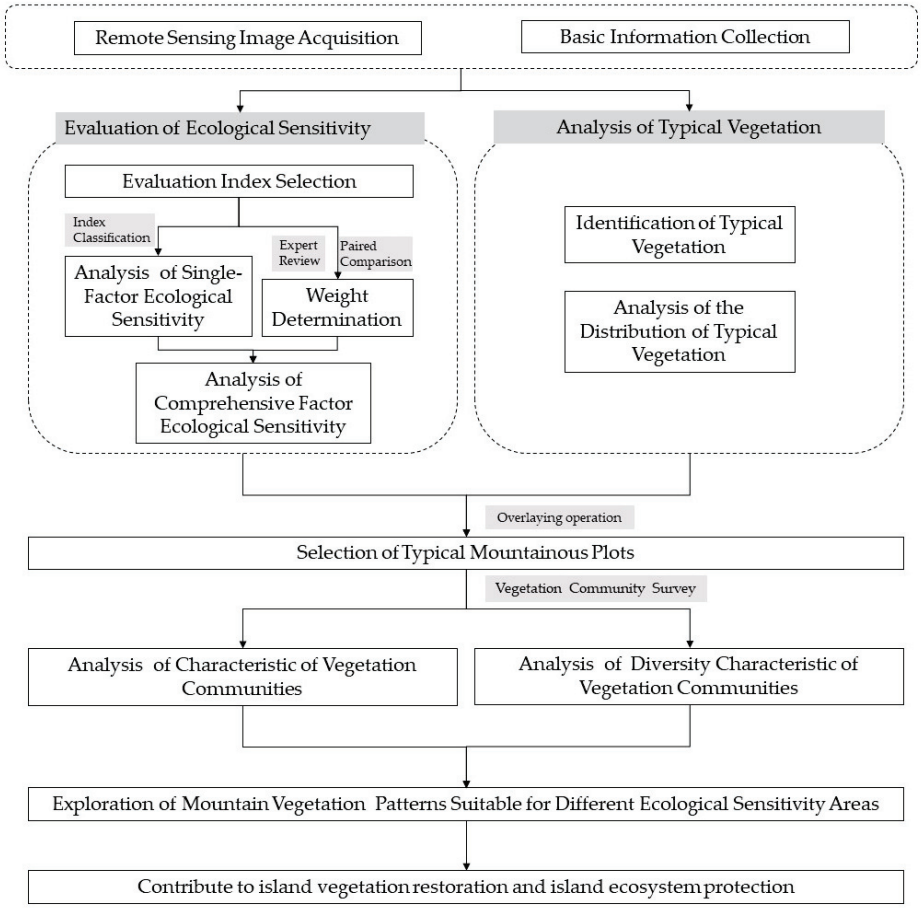



**Figure 1.** Flowchart of the study.

## 2. Materials and Methods

### *2.1. Study Area*

#### 2.1.1. Location and Climate

Pingtan Island is situated in the eastern sea of China, at a latitude range of 25°15′ to 25°45′ N and a longitude range of 119°32′ to 120°10′ E (Figure 2). It borders the Taiwan Strait to the east and is separated by the Haitan Strait to the west. Pingtan Island experiences a southern subtropical semi-moist marine monsoon climate, characterized by an average annual temperature ranging from 19.0 to 19.9 °C and average annual precipitation between 900 and 1200 mm. The island lacks rivers but features 46 seasonal creeks [24]. The average annual wind speed is 6.9 m/s, with 125 days experiencing gale force 7 or above throughout the year. Northeasterly winds prevail, except in summer, when southwesterly winds are prevalent [16].

#### 2.1.2. Topography and Geomorphology

Pingtan Island features elevated terrain in the north and south, characterized by undulating hills and low mountains, with the central region exhibiting lower elevation, primarily comprising a marine plain topography [2]. The mountainous and hilly areas are primarily divided into three sections, namely, northeast, northwest, and southern regions, covering a total area of 159 km$^2$, representing 42% of the total land area. The elevations in the northeastern mountainous region are mostly above 200 m, ranging between 100 and 180 m in the northwestern mountainous region and varying from 100 to 250 m above

sea level in the southern mountainous region. Pingtan Island is located at the northeast terminus of the Changle–Zhao'an active fault belt, and the rock outcrop is mainly of igneous origin from the late Yanshanian. Approximately 66% of the total island area is covered by aeolian sand, contributing to the formation of a typical coastal aeolian geomorphic landscape in southern China [25].

#### 2.1.3. Soils and Plants

Pingtan soils have a total of 6 soil classes, 25 soil genera, and 34 soil species, which are commonly characterized by thin soil layers, low nutrient content, and a more obvious vertical distribution of zonal soils [26]. The island's soil is dominated by brick-red loamy red soil (46%), coastal aeolian sandy soil (23.3%), and saline soil [27], followed by paddy soil, red soil, and alluvial soil. The woodland soils belong to three soil classes: brick-red loamy red soil, coastal aeolian sandy soil, and saline soil, with a total of five subclasses and eight soil genera. The soils in the main plant communities are all acidic, and the closer they are to the coastline, the less acidic they are [28]. The soil pH value, soil nitrogen content, organic matter content, available potassium content, and altitude have important effects on the distribution of communities [29].

Afforestation and greening efforts have significantly increased Pingtan's forest coverage, rising from 0.3% in 1949 to 29% in 2008 and reaching 37.2% in 2019. The greening coverage of the built-up area has reached 40.84% (2019). However, due to natural constraints, the construction of ecological landscape forests on Pingtan Island still faces challenges, resulting in poor silvicultural conditions [23]. The predominant plant species include island protection forest species, notably *Acacia confusa*, *Pinus thunbergii*, *Casuarina equisetifolia*, and *Pinus elliottii*, as well as some ornamental garden plants.

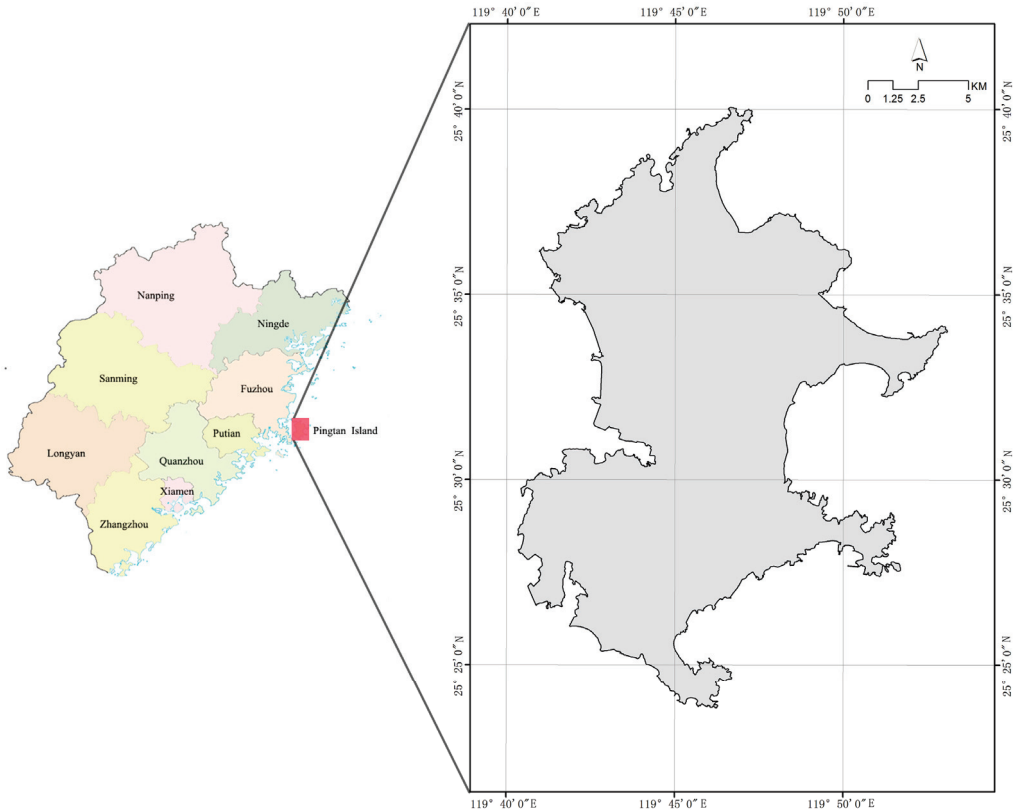



**Figure 2.** Location of study area.

### *2.2. Datasets*

The data for this study were sourced from the geospatial data cloud (http://www.gscloud.cn/ accessed on 10 December 2023), encompassing the 2020 Landsat OLI_TIRS remote sensing image of Pingtan Island with a resolution of 30 m × 30 m. Additionally, the dataset included the 30 m Pingtan Data Elevation Model (DEM), the 2020 Forestry Second Survey data of Pingtan, the Pingtan County Forest Vegetation Survey Report (1985), and meteorological data spanning the past 50 years in Pingtan (retrieved from the China Meteorological Data Network), among other sources.

### *2.3. Methods*

#### 2.3.1. Evaluation of Ecological Sensitivity

Selection of Ecological Sensitivity Indicators

Given the prevalence of the northeast wind on Pingtan Island from October to April of the succeeding year and the island's maximum elevation reaching 438.7 m, factors such as elevation, slope, and slope direction exert a considerable influence on ecological elements, including plant communities, soil, and water [30,31]. Among these factors, wind significantly affects plants. Due to challenges in obtaining measured data, the wind environment is simulated for an ideal terrain [13], although adjustments are made based on actual observations. The impact of anthropogenic interference on the ecological environment is predominantly evident in the land use type. Drawing on previous studies [5,7,32] and taking into account the ecological conditions of Pingtan Island, a set of ecological sensitivity evaluation factors for Pingtan Island was initially formulated, and expert consultation was conducted. Ultimately, eight factors, namely, elevation, slope, slope direction, vegetation coverage, soil texture, water environment, wind environment, and land use type, were selected to construct the ecological sensitivity evaluation system for Pingtan Island.

Quantitative Decomposition of Ecological Sensitivity Indicators

Quantitative data for each factor, except for the wind environment, were obtained through remote sensing imagery, second forestry survey data, and field research. Given the complexity of the wind environment on Pingtan Island and the extensive research scope, this study employed Computational Fluid Dynamics (CFD) software, such as Phoenics 2019, to simulate the wind environment. This involved combining meteorological data from the past 50 years on Pingtan Island. The specific processes included the following steps: (1) Contour extraction. Contour lines were extracted using ArcGIS 10.5 software. (2) Pre-experimentation with local and regional wind environment simulations. The model of Wangye Mountain was established in AutoCAD and SketchUp and then simulated in Phoenics to determine the most suitable simulation software. (3) Contour thinning and modeling. Based on the standard of setting the contour below 100 m above sea level to 10 m and the contour above 100 m to 20 m for thinning treatment, SketchUp2019 sandbox tools were used to generate the contour model of Pingtan Island. (4) Wind field grid setting. The grid density was gradually increased from both ends to the middle through several simulation iterations to minimize errors generated by wind speed decay during the calculation. (5) Parameter setting. Parameters such as NNE wind direction, 13.9 m/s wind speed, and 1.5 m height near the ground were adopted to simulate the wind environment.

Grading of Ecological Sensitivity Indicators

Factor assignment is based on the "principle of largeness" and the ecological "principle of least restriction". The evaluation indicators are categorized into 5 levels based on the degree of importance, with each factor level assigned a uniform score to facilitate horizontal comparisons. The final ecological sensitivity evaluation system established for Pingtan Island is presented in Table 1.

**Table 1.** Ecological sensitivity evaluation of Pingtan Island.

| Target Layer | Indicator Layer | Factor Layer | Criteria for Assigning Points | Degree Value | Degree of Ecological Sensitivity |
|---|---|---|---|---|---|
| Ecological Sensitivity Evaluation of Pingtan Island | Natural Factors | Elevation | 0–50 m | 1 | Ecological insensitivity |
| | | | 50–100 m | 3 | Slight ecological sensitivity |
| | | | 100–150 m | 5 | Moderate ecological sensitivity |
| | | | 150–250 m | 7 | High ecological sensitivity |
| | | | ≥250 m | 9 | Extreme ecological sensitivity |
| | | Slope | ≤5° | 1 | Ecological insensitivity |
| | | | 5–15° | 3 | Slight ecological sensitivity |
| | | | 15–25° | 5 | Moderate ecological sensitivity |
| | | | 25–35° | 7 | High ecological sensitivity |
| | | | ≥35° | 9 | Extreme ecological sensitivity |
| | | Slope direction | South, Flat Slope | 1 | Ecological insensitivity |
| | | | Southwest, southeast | 3 | Slight ecological sensitivity |
| | | | West | 5 | Moderate ecological sensitivity |
| | | | Northwest, east | 7 | High ecological sensitivity |
| | | | North, northeast | 9 | Extreme ecological sensitivity |
| | | Vegetation coverage | 0–0.2 | 1 | Ecological insensitivity |
| | | | 0.2–0.4 | 3 | Slight ecological sensitivity |
| | | | 0.4–0.6 | 5 | Moderate ecological sensitivity |
| | | | 0.6–0.8 | 7 | High ecological sensitivity |
| | | | >0.8 | 9 | Extreme ecological sensitivity |
| | | Soil texture | Others | 1 | Ecological insensitivity |
| | | | Brick-red loamy red soil | 3 | Slight ecological sensitivity |
| | | | Lateritic red soil | 5 | Moderate ecological sensitivity |
| | | | Red soil | 7 | High ecological sensitivity |
| | | | Coastal aeolian sandy soil and saline soil | 9 | Extreme ecological sensitivity |
| | | Water environment | >500 m buffers | 1 | Ecological insensitivity |
| | | | 200–500 m buffers | 3 | Slight ecological sensitivity |
| | | | 100–200 m buffers | 5 | Moderate ecological sensitivity |
| | | | 50–100 m buffers | 7 | High ecological sensitivity |
| | | | Reservoirs and lakes and within their 50 m buffers | 9 | Extreme ecological sensitivity |
| | | Wind environment | 0–9 m/s | 1 | Ecological insensitivity |
| | | | 9–15 m/s | 3 | Slight ecological sensitivity |
| | | | 15–18 m/s | 5 | Moderate ecological sensitivity |
| | | | 18–27 m/s | 7 | High ecological sensitivity |
| | | | 27–48 m/s | 9 | Extreme ecological sensitivity |
| | Human Factors | Land use type | Building land | 1 | Ecological insensitivity |
| | | | Bare ground | 3 | Slight ecological sensitivity |
| | | | Farmland | 5 | Moderate ecological sensitivity |
| | | | Woodland, grassland | 7 | High ecological sensitivity |
| | | | Water | 9 | Extreme ecological sensitivity |

Determination of Ecological Sensitivity Evaluation Indicator Weights

A paired comparison test and the expert consultation method were used to determine the weights of each evaluation factor. The results indicated the following weights for each factor: elevation 0.118, slope 0.074, slope direction 0.094, vegetation coverage 0.136, soil texture 0.193, water environment 0.081, wind environment 0.162, and land use type 0.143.

Spatial Overlay Analysis of Ecological Sensitivity of Composite Factors

The spatial analysis function of ArcGIS was employed to overlay the 8 factor indices and their corresponding weight values. This process calculated the comprehensive index of ecological sensitivity for Pingtan Island and reclassified it into a 5-level comprehensive ecologically sensitive area.

2.3.2. Sample Plot Selection

Determination of Typical Plant Communities on Pingtan Island

Utilizing data from the second forestry survey, the main plant communities on Pingtan Island were organized with the assistance of ArcGIS, providing a reference basis for subsequent sample plot selection. As presented in Table 2, the main plant communities on Pingtan Island consist of five species, with *Acacia confusa* plant communities covering a total area of 38.526% of the island. The research findings suggested that *Eucalyptus robusta* plant communities have limited landscape ecological benefits. Therefore, this study opted to focus on the four most typical plant communities—*Pinus thunbergii*, *Pinus elliottii*, *Acacia confusa*, and *Casuarina equisetifolia*—for further investigation.

**Table 2.** Area of main plant communities in Pingtan.

| No. | Plant Community | Size ($km^2$) | Percentage (%) |
|---|---|---|---|
| 1 | *Pinus thunbergii* | 3.782 | 1.199 |
| 2 | *Pinus elliottii* | 1.617 | 0.513 |
| 3 | *Eucalyptus robusta* | 2.965 | 0.940 |
| 4 | *Acacia confusa* | 67.210 | 21.307 |
| 5 | *Casuarina equisetifolia* | 45.952 | 14.567 |

Typical Sample Site Selection Based on Typical Plants and Ecological Sensitivity

The survey identified that the aforementioned four typical plant communities are more extensively distributed in Jun Mountain, Wangye Mountain, and Niuzhai Mountain, displaying a certain degree of representativity. Simultaneously, an overlay analysis revealed that the mountains on Pingtan Island are predominantly situated in moderate, high, and extreme ecologically sensitive areas. Consequently, this study designated these three mountains as the primary research areas and ultimately selected typical sample plots based on the three types of ecologically sensitive areas for investigation. In the end, 33 research plots were determined, as depicted in Figure 3.

Plant Community Survey Methods

The investigation employed typical plant community survey methods for basic information gathering [33]. Tree-related information, such as names, growth conditions, canopy density, diameter at breast height, height, and other details, were recorded using a circumference ruler and Leica laser rangefinder D81 (LeicaDISTOD5, Heerbrugg, Switzerland) for trees (diameter at breast height $\geq$ 3 cm or tree height $\geq$ 3 m) and other species in the plot [34]. In addition, small quadrats were randomly selected from each forest quadrat to measure shrub layer plants (5 m $\times$ 5 m) and ground cover plants (1 m $\times$ 1 m). Information, including the number, height, crown width, coverage, name, and other relevant details of shrubs and herbs, was documented.

Plant communities were classified based on plant community ecological principles [33]. The top five plant species with significant values were determined by calculating the importance values, leading to the identification of communities dominated by dominant species.

(**a**) Niuzhai Mountain

**Figure 3.** *Cont.*

(**b**) Wangye Mountain

**Figure 3.** *Cont.*

(**c**) Jun Mountain

**Figure 3.** Typical plot distribution map of Pingtan Island.

2.3.3. Geostatistical Analysis

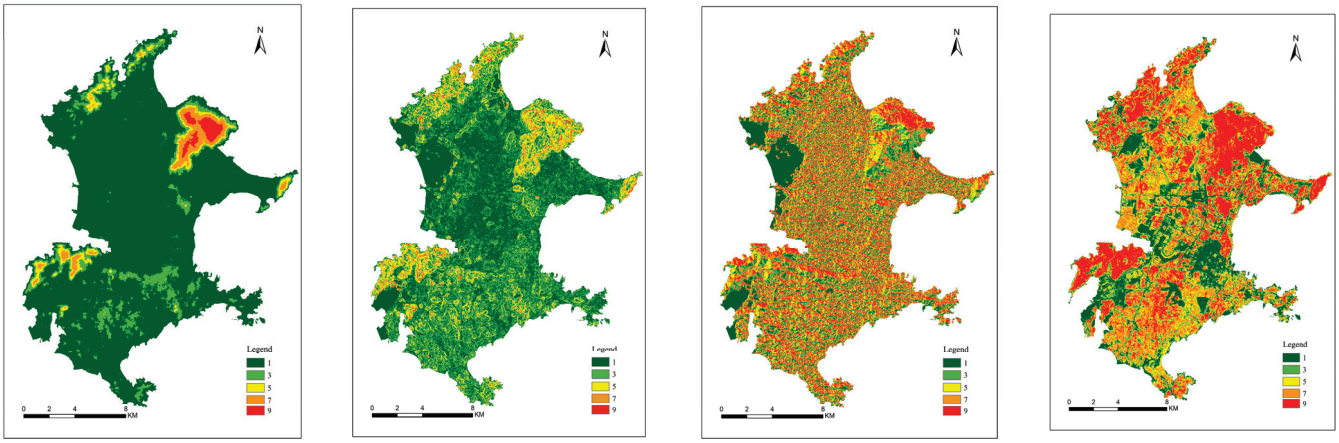
The data analysis in this study encompassed the determination of species importance values and species diversity. The species importance value determination method was utilized to measure the trees, shrubs, and grass layers individually. The comprehensive importance value was obtained. Owing to the straightforward structural composition of the surveyed island plant communities and the conspicuous dominance of certain species, we designated the dominant species as the foundational components for community establishment. The classification of a plant community was determined based on one or more species with the highest importance value [35], and the group average clustering method was employed to classify plant communities. Species diversity was measured according to the method outlined by Ma et al. [36], incorporating indicators such as the Margalef index, Shannon–Wiener index, Simpson index, and Pielou index.

## 3. Results

### *3.1. Analysis of Ecological Sensitivity Evaluation of Pingtan Island*

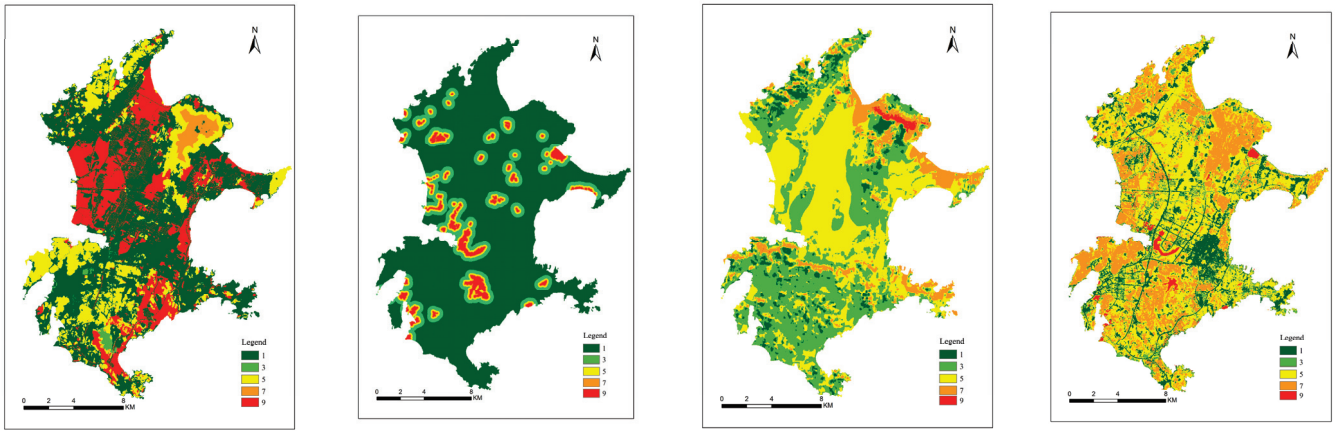
#### 3.1.1. Single-Factor Ecological Sensitivity Analysis

Figure 4 illustrates the ecological sensitivity characteristics of various factors. Both the elevation and slope of Pingtan Island are predominantly characterized by insensitivity and slight sensitivity, accounting for 93.03% and 85.65%, respectively, indicating a relatively gentle overall terrain. The slope orientation is evenly distributed, with high sensitivity (24.15%) and slight sensitivity (24.11%) dominating, particularly for northwest and east slope orientations, as well as southwest and southeast slope orientations. Vegetation coverage is mainly characterized by extreme sensitivity (28.23%) and high sensitivity (23.54%), primarily located in typical mountain areas, some lower mountains, and forest belts, with a lower percentage in urban built-up areas and certain coastal regions, signifying favorable vegetation coverage on Pingtan Island. The soil is mostly insensitive (53.19%), prevalently in cultivated land and urban built-up areas. This is followed by moderate and extreme sensitivities (21.96% and 21.46%, respectively), distributed in areas below 200 m in elevation, in the locations of major windbreaks, and near the western coast. The water environment is dominated by insensitivity (77.48%). Due to topographical constraints, the surface water on Pingtan Island is limited, exerting a minor impact on island habitats. Wind environment sensitivity is mainly moderate (42.32%) and slight (41.44%), corresponding to wind speeds primarily between 15 and 18 m/s and between 9 and 15 m/s, with extreme sensitivity (0.64%) concentrated in the five major vents. The land use type shows predominantly moderate sensitivity (48.34%) and high sensitivity (27.91%), encompassing arable land, woodland, and grassland, while extreme sensitivity (1.72%) is minimal. Despite being relatively water-scarce, the water areas are the most fragile, prone to drying up and disappearing.



(**a**) (**b**) (**c**) (**d**)

**Figure 4.** *Cont.*



(**e**) (**f**) (**g**) (**h**)

**Figure 4.** Single-factor ecological sensitivity analysis maps of Pingtan Island. (**a**) Elevation Grading Map, (**b**) Slope Grading Map, (**c**) Slope Direction Grading Map, (**d**) Vegetation Coverage Grading Map, (**e**) Soil Texture Grading Map, (**f**) Water Environment Grading Map, (**g**) Wind Environment Grading Map, (**h**) Land Use Type Grading Map. Note: 1 represents ecological insensitivity; 3 represents slight ecological sensitivity; 5 represents moderate ecological sensitivity; 7 represents high ecological sensitivity; 9 represents extreme ecological sensitivity.

#### 3.1.2. Comprehensive Factor Ecological Sensitivity Analysis

As shown in Table 3 and Figure 5, the comprehensive ecological sensitivity of Pingtan Island is presented as follows: slightly ecologically sensitive area (35.72%) > moderate ecologically sensitive area (33.99%) > high ecologically sensitive area (18.02%) > ecologically insensitive area (10.79%) > extreme ecologically sensitive area (1.48%).

**Table 3.** Comprehensive ecological sensitivity analysis of Pingtan Island.

| No. | Degree of Ecological Sensitivity | Size ($km^2$) | Percentage (%) |
|---|---|---|---|
| 1 | Ecological insensitivity | 29.65 | 10.79 |
| 2 | Slight ecological sensitivity | 98.18 | 35.72 |
| 3 | Moderate ecological sensitivity | 93.41 | 33.99 |
| 4 | High ecological sensitivity | 49.53 | 18.02 |
| 5 | Extreme ecological sensitivity | 4.07 | 1.48 |

The slightly ecologically sensitive areas are primarily situated in some of the lower hilly areas in the central and western parts of the island, interspersed with slightly sensitive areas. The moderate ecologically sensitive areas include low mountainous rural settlements around the central 36-foot lake and the low-slope areas of slightly higher mountains, such as Jun Mountain and Wangye Mountain, which are less affected by wind and offer better habitats. The high ecologically sensitive areas are mainly the elevated regions of certain mountains, some lower-elevation areas of windbreaks along the seashore, encompassing more windward areas, and some mid-slope leeward areas. The ecologically insensitive areas mainly comprise urban built-up areas and development zones in the central and southern parts of the island, along with rural settlements in the central and northern regions. The extreme ecologically sensitive areas are primarily located on the windward slopes and ridges of Jun Mountain, Wangye Mountain, and Niuzhai Mountain at an elevation of about 200 m.

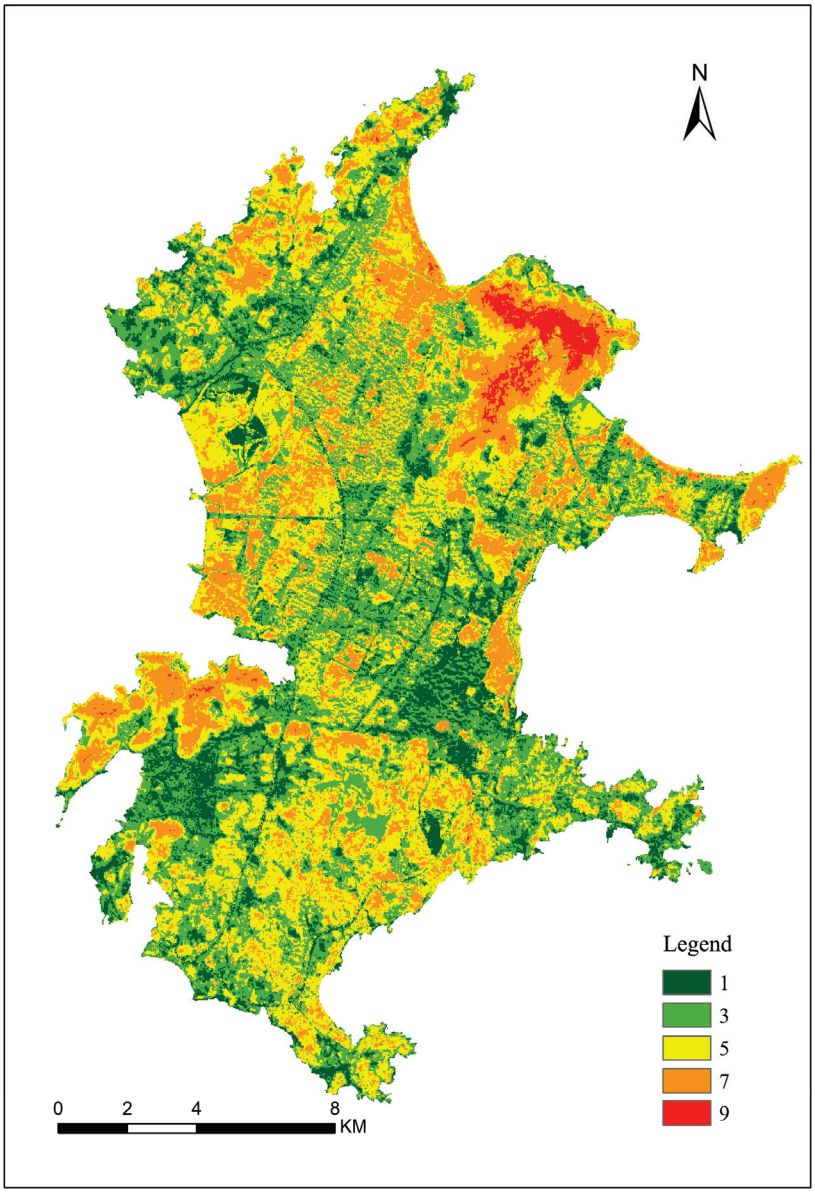



**Figure 5.** Comprehensive ecological sensitivity. Note: 1 represents ecological insensitivity; 3 represents slight ecological sensitivity; 5 represents moderate ecological sensitivity; 7 represents high ecological sensitivity; 9 represents extreme ecological sensitivity.

### *3.2. Analysis of Montane Plant Communities in Various Ecologically Sensitive Areas of Pingtan Island*

#### 3.2.1. Analysis of the Species Composition of Montane Plant Communities in Various Ecologically Sensitive Areas

A total of 93 species (82 genera and 47 families) of mountain plants were investigated in 33 sample sites. Among the 93 species, 13 were trees, 35 were shrubs, and 45 were herbs. There are 2 families with 6–9 species (17.28%), 13 families with 2–5 species (53.09%), and 24 families with 1 species (29.63%). Among them, 59 species (54 genera and 38 families) were found in moderate ecologically sensitive areas, 81 species (73 genera and 45 families) in high sensitive areas, and 33 species (32 genera and 30 families) in extreme ecologically sensitive areas (Table A1).

3.2.2. Analysis of Dominant Species of Montane Plant Communities in Various Ecologically Sensitive Areas

A total of 13 *A. confusa* forests, 4 *C. equisetifolia* forests, 6 *P. thunbergii* forests, 2 *P. elliottii* forests, 1 *Schima superba* forests, 3 *A. confusa* scrubs, 3 *E. emarginata* scrubs, and 1 *P. thunbergii* scrub were identified in the 33 sample plots (Table A2).

In the moderate ecologically sensitive area, J2, J3, N2, N3, and W3 sample plots all have *A. confusa* forests as constructive species, J6 is a pure forest of C. equisetifolia, J8 is a forest of *S. superba* mixed with *A. confusa* and *Cunninghamia lanceolata*, and J16 is a forest of *P. thunbergii*. Among the high ecologically sensitive areas, the group species in plots J1, J15, N1, W1, W2, W5, W6, and W7 are all *A. confusa* forests; J13, N4, and N5 are *P. thunbergii* forests; J7 and J9 are pure and mixed *P. elliottii* forests, respectively; and J4, J5, and N7 are pure forests of *C. equisetifolia*. The rest of the sample plots are missing the tree layer: J14, N6, and W10 are *A. confusa* scrub, W4 is *P. thunbergii* scrub, W8 and W9 are *E. emarginata* scrub, and the various plant species in the scrubs are auxiliary species to each other. In the extreme ecologically sensitive area, J10 and J11 are *P. thunbergii* forests, and J12 is *E. emarginata* scrub.

3.2.3. Characterization of Montane Plant Communities in Various Ecologically Sensitive Areas

Characterization of Plant Communities

The characterization of the various sensitive areas revealed that the canopy density (CD) and mean height of tree layer (MHTL) exhibited a pattern of moderate ecologically sensitive areas > high ecologically sensitive areas > extreme ecologically sensitive areas. The mean diameter at breast height (MDBH) and the mean height of shrub layer (MHSL) have a pattern of high ecologically sensitive areas > moderate ecologically sensitive areas > extreme ecologically sensitive areas. The mean height of herb layer (MHHL) was the highest in the extreme ecologically sensitive area (Table 4).

**Table 4.** Means and standard deviations of characteristics of plant communities in various ecologically sensitive areas.

| Ecologically Sensitive Area | CD | MDBH (cm) | MHTL (m) | MHSL (cm) | MHHL (cm) |
|---|---|---|---|---|---|
| Moderate ecologically sensitive areas | 74.00 ± 30.41 | 8.17 ± 3.15 | 4.98 ± 1.84 | 0.61 ± 0.38 | 0.29 ± 0.08 |
| High ecologically sensitive areas | 49.59 ± 42.61 | 8.42 ± 6.99 | 4.72 ± 3.89 | 0.71 ± 0.32 | 0.27 ± 0.15 |
| Extreme ecologically sensitive areas | 33.33 ± 35.12 | 4.66 ± 4.04 | 1.99 ± 1.77 | 0.59 ± 0.05 | 0.29 ± 0.26 |

Note: CD represents canopy density; MDBH represents mean diameter at breast height; MHTL represents mean height of tree layer; MHSL represents mean height of shrub layer; MHHL represents mean height of herb layer.

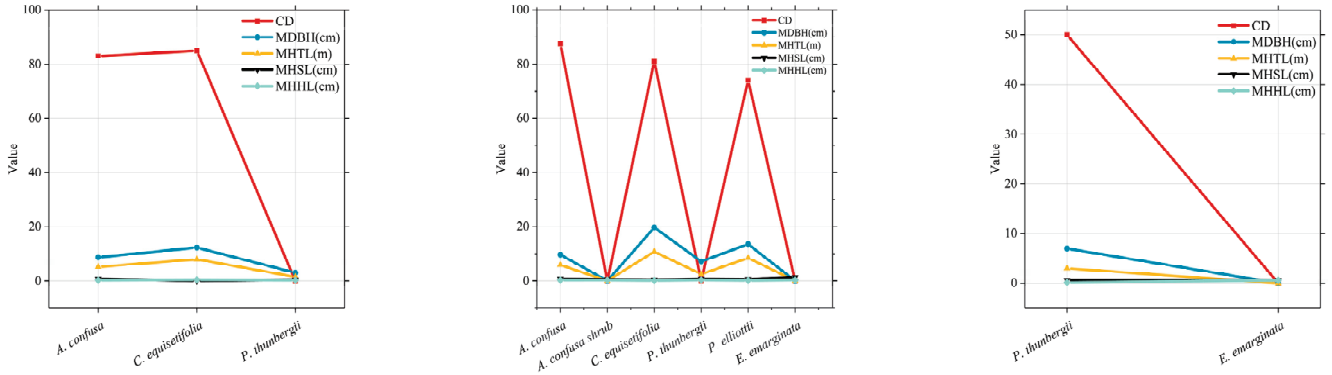
Concerning different plant communities, the tree layer exhibited better growth conditions in *A. confusa* and *C. equisetifolia* forests, while *P. thunbergii* forests demonstrated the lowest performance in CD, MDBH, and MHTL. Shrub layer and grass layer growth heights were optimal in *E. emarginata* scrub, while shrub layer growth was minimal in *C. equisetifolia* forests, and herb layer growth was lowest in *P. elliottii* forests (Table 5).

**Table 5.** Means and standard deviations of characteristics of various plant communities.

| Plant Community | CD | MDBH (cm) | MHTL (m) | MHSL (cm) | MHHL (cm) |
|---|---|---|---|---|---|
| *A. confusa* forest | 85.77 ± 5.09 | 9.31 ± 1.99 | 5.61 ± 0.91 | 0.75 ± 0.34 | 0.29 ± 0.15 |
| *C. equisetifolia* forest | 82.0 ± 8.71 | 17.86 ± 6.40 | 10.10 ± 1.87 | 0.33 ± 0.18 | 0.21 ± 0.18 |
| *P. thunbergia* forest | 16.67 ± 28.75 | 6.44 ± 1.80 | 2.48 ± 0.63 | 0.62 ± 0.15 | 0.27 ± 0.12 |
| *P. elliottii* forest | 74.0 ± 5.66 | 13.55 ± 6.46 | 8.47 ± 2.75 | 0.56 ± 0.06 | 0.16 ± 0.23 |
| *A. confuse* scrub | 0 | 0 | 0 | 0.55 ± 0.12 | 0.33 ± 0.05 |
| *E. emarginata* scrub | 0 | 0 | 0 | 1.08 ± 0.49 | 0.41 ± 0.19 |

Note: CD represents canopy density; MDBH represents mean diameter at breast height; MHTL represents mean height of tree layer; MHSL represents mean height of shrub layer; MHHL represents mean height of herb layer.

In moderate ecologically sensitive areas, the CD, MDBH, and MHTL were higher for *C. equisetifolia* forests and the lowest for *P. thunbergii* forests. The shrub layer height was the highest in *A. confusa* forests and the lowest in *C. equisetifolia* forests. The herb layer was taller in *C. equisetifolia* forests. In high ecologically sensitive areas, *A. confusa* and *C. equisetifolia* forests had high levels of CD, and *C. equisetifolia* and *P. elliottii* forests had higher MDBH and MHTL. The shrub layer height reached its maximum in *E. emarginata* scrub, the herb layer was taller in *P. thunbergii* forests, and both the shrub and herb layers were at their minimum in *C. equisetifolia* forests. In the extreme ecologically sensitive areas, the underlying characteristic data were highest for *P. thunbergii* forests, except for the herb layer height. Additionally, shrub layer heights were similar (Figure 6).




(**a**) (**b**) (**c**)

**Figure 6.** Plant community characteristics in various ecologically sensitive areas. (**a**) Moderate ecological sensitivity, (**b**) High ecological sensitivity, (**c**) Extreme ecological sensitivity. Note: CD represents canopy density; MDBH represents mean diameter at breast height; MHTL represents mean height of tree layer; MHSL represents mean height of shrub layer; MHHL represents mean height of herb layer.

Species Diversity

As depicted in Table 6, the Shannon–Wiener index, Pielou index, Margalef index, and Simpson index in the three sensitive areas exhibited an upward trend with increasing ecological sensitivity.

**Table 6.** Means and standard deviations of plant community diversity in various ecologically sensitive areas.

| Ecologically Sensitive Area | Shannon–Wiener | Pielou | Margalef | Simpson |
|---|---|---|---|---|
| Moderate ecologically sensitive areas | 2.25 ± 0.50 | 0.82 ± 0.12 | 3.13 ± 0.91 | 0.83 ± 0.12 |
| High ecologically sensitive areas | 2.27 ± 0.47 | 0.84 ± 0.08 | 3.24 ± 1.08 | 0.86 ± 0.08 |
| Extreme ecologically sensitive areas | 2.51 ± 0.22 | 0.89 ± 0.03 | 3.33 ± 0.85 | 0.90 ± 0.02 |

Among the various plant communities, all four diversity indices for *A. confusa* forests were the highest, with scrub diversity surpassing that of forests. Subsequently, *E. emarginata* scrub exhibited higher Shannon–Wiener and Simpson indices, while *P. thunbergii* forests showed a higher Margalef index. In contrast, the combined species diversity of *C. equisetifolia* and *P. elliottii* forests was comparatively low (Table 7).

**Table 7.** Means and standard deviations of species diversity of various plant communities.

| Plant Community | Shannon–Wiener | Pielou | Margalef | Simpson |
|---|---|---|---|---|
| *A. confusa* forest | 2.42 ± 0.07 | 0.87 ± 0.01 | 3.38 ± 0.18 | 0.88 ± 0.01 |
| *C. equisetifolia* forest | 1.64 ± 0.32 | 0.86 ± 0.05 | 1.95 ± 0.81 | 0.75 ± 0.07 |
| *P. thunbergia* forest | 2.38 ± 0.12 | 0.83 ± 0.05 | 3.50 ± 0.20 | 0.89 ± 0.01 |
| *P. elliottii* forest | 1.72 ± 0.34 | 0.79 ± 0.08 | 2.10 ± 0.57 | 0.77 ± 0.09 |
| *A. confuse* scrub | 2.69 ± 0.23 | 0.86 ± 0.04 | 4.39 ± 0.58 | 0.91 ± 0.02 |
| *E. emarginata* scrub | 2.45 ± 0.07 | 0.85 ± 0.01 | 3.13 ± 0.38 | 0.89 ± 0.00 |

Among the moderate ecologically sensitive areas, the Margalef index exhibited higher values in *A. confusa* forests, while the Shannon–Wiener, Pielou, and Simpson indices were comparable between *P. thunbergii* and *A. confusa*, and all were lowest in *C. equisetifolia* forests. Within the high ecologically sensitive areas, the Shannon–Wiener, Margalef, and Simpson indices reached their peaks in *A. confusa* scrub and were lower in both *P. elliottii* and *C. equisetifolia* forests. The Pielou index recorded its highest value in *C. equisetifolia* forests, followed by *A. confusa* forests and scrubs, and was at its lowest in *P. thunbergii* forests. Among extreme ecologically sensitive areas, all four diversity indices attained their highest values in *P. thunbergii* forests (Figure 7).

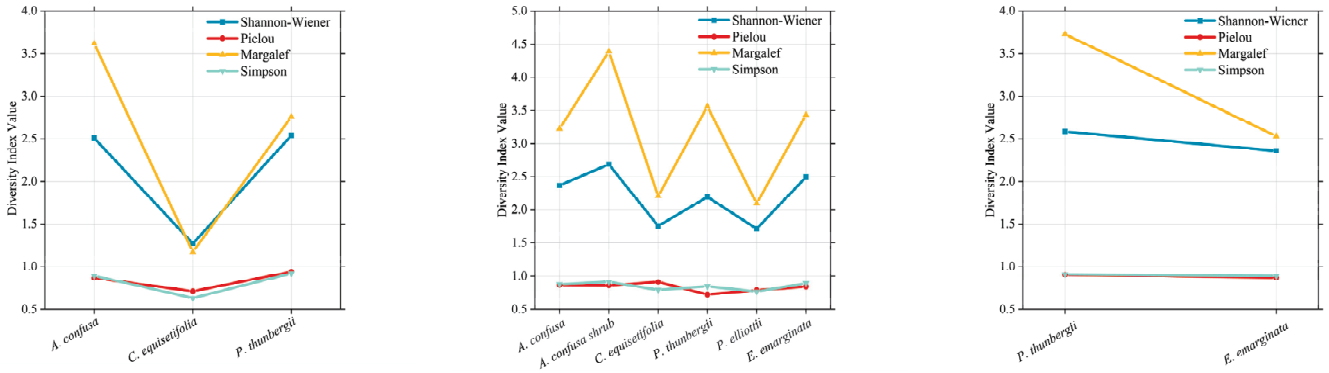



**Figure 7.** Diversity indices of plant community in various ecologically sensitive areas. (**a**) Moderate ecological sensitivity, (**b**) High ecological sensitivity, (**c**) Extreme ecological sensitivity.

## 4. Discussion

### *4.1. Ecological Sensitivity Characteristics of Pingtan Island*

The results of the ecological sensitivity evaluation of Pingtan Island reveal that the elevation, slope, soil, and water on Pingtan Island exhibit a low level of ecological sensitivity, while vegetation coverage demonstrates high ecological sensitivity. The wind environment is categorized as medium-low ecological sensitivity and the land use type as medium-high ecological sensitivity, and the distribution of the slope direction is relatively uniform. The results of the single-factor weight analysis indicate that the soil, wind environment, and land use type are the more influential factors, aligning with previous research findings that attribute the vulnerability of Pingtan Island's ecological environment to a combination of natural conditions and human activities [17]. It is recommended that ecological protection and improvement efforts on Pingtan Island prioritize the enhancement of soil conditions, the wind environment, and the optimization of land use types. Specifically, the spatial distribution analysis of soil sensitivities on Pingtan Island highlights severe salinization and sanding in the four vents, necessitating targeted prevention measures. In the subsequent stages of plant landscape construction, the ecological protection role of windbreaks should be reinforced. Considering the prevailing northeasterly winds on Pingtan Island, due

north and northeasterly slopes emerge as the primary windward areas. Among them, the Changjiang'Ao windbreak, where the east and west of the stream have the maximum wind frequency and the dominant wind flow through them, is the location of the concentrated distribution of perennial wind resources. This area should be judiciously utilized for wind energy and plant configuration planning. Conversely, lower wind speeds are observed in the southern and western parts of the island, most of the southern part of Jun Mountain, the northern mountainous areas, and some of the lower-elevation areas, indicating that major mountainous terrains play a significant role in reducing wind speeds [37]. Water is the most sensitive land use type on Pingtan Island due to topographical constraints, as is common for many islands globally, given their limited freshwater resources [2]. Despite this limitation, water is indispensable to the ecosystem. Woodland ranks as the second most sensitive type due to the inherent difficulty in restoring mountains once destroyed. Moreover, woodlands contribute significantly to ecosystem regulation and supporting services. This is particularly crucial for islands, where plants with specialized functions such as wind protection and sand fixation hold heightened importance.

From the perspective of comprehensive ecological sensitivity, Pingtan Island is dominated by three categories: slightly ecologically sensitive areas (35.72%), moderate ecologically sensitive areas (33.99%), and extreme ecologically sensitive areas (18.02%). The ecologically insensitive areas are primarily situated in regions with notable human activity, featuring low elevation, flat terrain, sparse vegetation, and robust resistance to disturbances. These areas permit relatively intense urban development and construction and are also the best areas for the diversification of plant landscape construction. The slightly ecologically sensitive areas encompass some mountainous and green regions where human activities introduce certain disturbances. Nevertheless, the ecosystems in these areas are more stable than those in insensitive regions. Consequently, a combination of plant and landscape development with human activities conducted in a moderate manner is feasible. The moderate ecologically sensitive areas include sporadic rural settlements with less human interference, featuring higher vegetation density compared to areas with lower sensitivity. Plant landscapes in these zones can be adjusted accordingly, with options such as forest phase modifications to enhance landscape effects. Additionally, localized forest recreational activities can be conducted in areas with suitable microclimatic environments. The high ecologically sensitive areas boast high ecological quality and are abundant in botanical landscape resources. These areas warrant improvements grounded in ecological protection and the enhancement of ecological landscapes. The vegetation in extreme ecologically sensitive areas experiences minimal human disturbance but is more susceptible to natural environmental factors such as wind and sun, leading to the stunted growth and desiccation of vegetation. These zones are primarily designated for ecological restoration and protection, with the goal of constructing a distinctive ecological landscape on the island.

The wind environment simulation in this study was conducted by simulating island-wide near-surface wind conditions of NNE 13.9 m/s (gale force 7) without accounting for the topography of plants and buildings. However, upon comparing these simulation results with field measurement data, a notable similarity is observed, affirming the feasibility of the wind environment simulation method employed in this study. This finding is intended to provide methodological support for future related studies. In practical applications, the presence of wooded areas and buildings across more extensive parts of the island, along with the potential for improved localized microclimatic environments in various ecologically sensitive areas due to ground plants and shading by buildings, necessitates further in-depth investigations into these localized microclimatic habitats. Future efforts should focus on refining both the model and observation conditions to enhance the overall reliability of the conclusions drawn. Given the variations in habitat characteristics among islands, those with limited conditions can consider referring to this model for the study of island habitats.

*4.2. Typical Plant Communities and Characteristics in the Mountains of Pingtan Island across Various Ecologically Sensitive Areas*

(1) Exploration of Composition and Dominant Species of Typical Mountain Plant Community

The survey revealed that the typical plant community in the mountains of Pingtan Island follows the order herb layer > shrub layer > tree layer, aligning with the stage dominated by the shrub–grass succession stage. This pattern is consistent with previous findings that herbs are generally considered to be more adept at colonization than woody plants [38]. This phenomenon can be ascribed to the impact of strong winds, rendering low-growing herbaceous plants more adaptable to this environment in comparison to taller trees and shrubs [21]. Soil conditions, climate, and other factors also contribute to these observed patterns. Among the various ecologically sensitive areas, the high ecologically sensitive areas exhibit characteristics such as a greater number of species and higher species diversity. However, the overall mountainous plant community on Pingtan Island remains relatively homogeneous, featuring a significant proportion of pure forests. There exists a certain degree of repetition and similarity in the plant communities across different ecologically sensitive areas. This phenomenon can be attributed to the unique habitat conditions of islands, where natural selection favors more adaptable native plant communities. Consequently, the plant community similarity is more pronounced.

The dominant species vary across different sensitive areas. The group species in moderate ecologically sensitive areas are all forests, dominated by *A. confusa* and *S. superba* forests. The high and extreme ecologically sensitive areas comprise both arborvitae forests and scrub. The high ecologically sensitive areas are dominated by *A. confusa*, *P. thunbergii*, *P. elliottii*, and *C. equisetifolia* forests, while the extreme ecologically sensitive areas are dominated by *P. thunbergii* forests and *E. emarginata* scrub. Observing the different ecologically sensitive areas, it is evident that with increasing elevation, there is a shift in dominance from *A. confusa* to *P. thunbergii* and finally to *E. emarginata*, indicating a successional pattern.

In general, the current montane plant community on Pingtan Island is less diverse, with a single structure and lower species diversity. This is due to the fact that, because of the need to adapt to habitats with persistent high winds and low soil nutrients, Pingtan Island has more wild herbaceous plants, and more plants tend to have smaller flowers, leaves, and fruits [21,39], with small and hairy, highly lignified, and fleshy leaves and more thorny shrubs and vines [40]. In the future, we should continue to screen suitable plants for mountainous areas with suitable local characteristics, strengthen the adaptability of plants to windy environments and infertile soils through domestication and introduction in order to increase the diversity of mountainous plants, and further strengthen the research on typical plant patterns in mountainous areas so as to enhance the significance of practical guidance.

(2) Characterization of Typical Mountain Plants

There are variations in the community characteristics of plant communities across different ecologically sensitive areas, which are characterized by the dominance of differentiated tree–shrub–herb layers. Trees exhibit superior growth in moderate ecologically sensitive areas, while high ecologically sensitive areas transition toward a tree–shrub community. Herbs grow better in extreme ecologically sensitive areas compared to other areas. These differences are associated with the habitat conditions in distinct sensitive areas, wherein shrubs, grasses, and other lower plants show better adaptation to the environment in higher-elevation areas [41].

The analysis of the different plant communities revealed that the tree growth of *C. equisetifoli* forests was more robust in both the moderate and high ecologically sensitive areas. However, the prominence of this dominant species has led to an excessive canopy density, creating unfavorable growing conditions for other smaller trees or lower plants. Consequently, shrub growth is minimal, and herbaceous growth is suboptimal. In the case of the *P. thunbergii* forest, its performance is moderate in both the moderate and high ecologically sensitive areas. It exhibits the lowest level of tree canopy density, but this

characteristic facilitates the provision of necessary light and other conditions for the growth of other plants. Therefore, shrubs and grasses within this forest exhibit better growth. The *E. emarginata* scrub predominantly occurs in high and extreme ecologically sensitive areas, where the absence of the tree layer allows shrubs and grasses to thrive due to increased sunlight availability and more favorable growing conditions. The findings from the species diversity study indicate that increased ecological sensitivity contributes to the species diversity of plant communities. However, the disparities in their species diversity were not statistically significant. This is attributed to the influence of environmental factors, including elevation, precipitation, wind speed, and soil, on island species diversity [42–45]. In the study area, the overall habitats do not vary significantly, which subsequently leads to small differences in overall species diversity.

Species diversity indicators exhibited more pronounced variations among plant communities. The Shannon–Wiener, Pielou, Margalef, and Simpson indices within *A. confusa* plant communities, particularly in *A. confus* scrub, are elevated. This phenomenon may be attributed to the interspersion of scrub with young trees. Young trees in the community increase the diversity of the shrub layer, and the plants are more light-adapted [29,46] The moderate and high ecologically sensitive areas exhibited a heightened degree of diversity in the context of *A. confusa*. This phenomenon may be attributed to the successional stage of the *A. confusa* community on the middle and lower slopes, encompassing both sun- and shade-loving plants. Furthermore, certain anthropogenic disturbances have created forest gaps in *A. confusa* forests, where the understory of shrubby *S. superba* and *Ficus formosana* receives increased light exposure, gaining a competitive advantage and developing into trees. This dynamic contributes to an augmentation in the diversity of this community. Additionally, the leeward slope location of *A. confusa* forests favors the growth of various plant types, as they are less affected by high winds. Pielou and Simpson indices were also high in *P. thunbergii* forests, indicating structural stability within the plant community [47], a characteristic linked to community succession patterns. The relatively low canopy density in *P. thunbergii* forests plays a role in supporting the growth of other sun-loving plants. The low species diversity of *C. equisetifolia* forests stems from a lack of diversity or very low diversity in the arboreal shrub layer. Although individual plant growth is robust, the extremely high canopy density creates unfavorable conditions for the growth of other sun-loving plants or lower scrubs, resulting in low species diversity. Additionally, the reduction in plant numbers can impede the provision of sufficient apoplastic material for microbial decomposition, subsequently leading to habitat deterioration and a decline in species diversity indices [29]. As ecological sensitivity increases, it signifies more pronounced ecological challenges. Based on the distribution patterns, it is observed that *P. thunbergii* forests on Pingtan Island are predominantly situated in uphill positions and northeast slope directions, implying their preference for more windward locations. This suggests that *P. thunbergii* forests exhibit enhanced adaptability to windy conditions and the overall environment. On the other hand, *P. thunbergii* forests also offer some shaded spaces, facilitating growth conditions for semi-sun-loving plants like *Melastoma candidum* and subsequently enhancing their overall diversity.

In terms of the amalgamation of characteristics and species diversity, the ideal ecological communities that are more stable in the mountains of Pingtan Island include *A. confusa* forests and scrubs, *E. emarginata* scrubs, *P. thunbergii* forests, etc. Conversely, those with lower composite characteristic indices were predominantly *C. equisetifolia* forests, *P. elliottii* forest communities, etc., consisting of pure forests with diminished species diversity and consequently exhibiting lower stability. Based on these findings, landscape construction in different sensitive areas can be implemented by referencing the corresponding plant community model, thereby providing a model reference for the landscape construction of other analogous islands and mountains.

## 5. Conclusions

The unique geographical location and environmental characteristics of islands have led to fragile ecosystems and distinctive features in plant communities. Therefore, it is crucial to delineate the characteristics of plant communities in various ecologically sensitive areas for the protection and sustainable development of island ecosystems. This paper focuses on Pingtan Island in Fujian Province, China, and draws the following conclusions: (1) A proficient approach to wind environment modeling and data acquisition for Pingtan Island is proposed. The outcomes of the ecological sensitivity evaluation conducted on this basis revealed that Pingtan Island exhibits an ecological sensitivity distribution pattern of slightly ecologically sensitive areas > moderate ecologically sensitive areas > high ecologically sensitive areas > ecologically insensitive areas > extreme ecologically sensitive areas. Key influencing factors include the soil texture (0.193), wind environment (0.162), and land use type (0.143). Accordingly, this paper proposes corresponding strategies for ecological environmental protection tailored to different ecologically sensitive areas. (2) The mountainous habitats of Pingtan Island are distributed in moderate, high, and extreme ecologically sensitive areas. This paper summarizes the characteristics of more stable montane plant communities within different ecologically sensitive areas through investigation and analysis. Overall, following the pattern of plant succession, herbs are the most abundant, followed by shrubs and, finally, trees. The number of plants increases with sensitivity. The base characteristics of trees are better in the moderate ecologically sensitive areas, and the high ecologically sensitive areas exhibit a trend toward tree–shrub communities. Among these two types of ecologically sensitive areas, *A. confusa* forests show the best overall ecological benefits in tree forests. *C. equisetifolia* forests, despite having superior tree-based characteristics, display lower species diversity, whereas *P. thunbergii* forests exhibit the opposite pattern. Additionally, the combined ecological benefits of *A. confusa* and *E. emarginata* scrubs are superior. Herbs thrive in extreme ecologically sensitive areas, showing the best combined ecological benefits with *P. thunbergii* forests.

This study encapsulates the ecological sensitivity characteristics of Pingtan Island as well as the characteristics of plant communities suitable for different ecologically sensitive areas and provides corresponding optimization strategies. The objective is to systematically undertake targeted initiatives for island plant restoration and ecosystem preservation, thereby fostering the sustainable development of the island's habitats.

**Author Contributions:** Conceptualization, J.L. (Jinyan Liu), J.L. (Junyi Li), G.D. and J.D.; methodology, J.L. (Jinyan Liu) and J.L. (Junyi Li); software, J.L. (Jinyan Liu), J.L. (Junyi Li) and D.C.; validation, J.L. (Jinyan Liu), J.L. (Junyi Li) and D.C.; formal analysis, J.L. (Jinyan Liu), J.L. (Junyi Li) and L.G.; investigation, J.L. (Jinyan Liu), J.L. (Junyi Li), D.C. and L.G.; resources, J.L. (Jinyan Liu), J.L. (Junyi Li), G.D. and J.D.; data curation, J.L. (Jinyan Liu), J.L. (Junyi Li) and L.G.; writing—original draft preparation, J.L. (Jinyan Liu) and J.L. (Junyi Li); writing—review and editing, J.L. (Jinyan Liu), J.L. (Junyi Li), G.D. and J.D.; visualization, J.L. (Jinyan Liu), J.L. (Junyi Li), D.C. and L.G.; supervision, J.L. (Jinyan Liu), J.L. (Junyi Li), G.D. and J.D.; project administration, G.D. and J.D.; funding acquisition, G.D. and J.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Green Urbanization across China and Europe: Collaborative Research on Key Technological Advances in Urban Forests, grant number 2021YFE0193200.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Appendix A

**Table A1.** Species composition of a typical sample site in the mountains of Pingtan Island.

| Sensitivity Zones | Number of Species (Families) | Family Name (Genus: Species) | Percentage (Family, Genus, Species) |
|---|---|---|---|
| Moderate ecologically sensitive area | 2–5 (11) | Labiatae (2:2), Pteridaceae (3:3), Gramineae (4:4), Apocynaceae (3:3), Thelypteridaceae (1:3), Malvaceae (2:2), Compositae (3:4), Rubiaceae (3:3), Rosaceae (2:4), Salicaceae (2:2), Umbelliferae (2:2) | 29%, 50%, 54% |
| | 1 (27) | Myrtaceae, Smilacaceae, Pentaphylacaceae, Lauraceae, Sapindaceae, Euphorbiaceae, Lygodiaceae, Pittosporaceae, Pinaceae Lindl., Asparagaceae, Caprifoliaceae, Thymelaeaceae, Rutaceae, Gleicheniaceae, Theaceae, Casuarinaceae, Cannabaceae, Menispermaceae, Celastraceae, Rhamnaceae, Asphodelaceae, Cupressaceae Bartling, Vitaceae, Moraceae, Leguminosae, Melastomataceae, Primulaceae | 71%, 50%, 46% |
| | 6–9 (2) | Gramineae (6:6), Compositae (7:7) | 4.4%, 18%, 16% |
| High ecologically sensitive area | 2–5 (13) | Labiatae (2:2), Leguminosae (4:4), Pteridaceae (3:5), Apocynaceae (3:3), Thelypteridaceae (1:3), Malvaceae (2:2), Rubiaceae (3:3), Rosaceae (2:3), Moraceae (2:3), Pinaceae Lindl. (1:2), Asparagaceae (3:3), Salicaceae (2:3), Umbelliferae (2:2) | 28.9%, 41%, 47% |
| | 1 (30) | Smilacaceae, Araliaceae, Pentaphylacaceae, Goodeniaceae, Lauraceae, Sapindaceae, Euphorbiaceae, Lygodiaceae, Pittosporaceae, Elaeagnaceae, Polygonaceae, Umbelliferae, Caprifoliaceae, Thymelaeaceae, Rutaceae, Gleicheniaceae, Theaceae, Casuarinaceae, Menispermaceae, Celastraceae, Rhamnaceae, Asphodelaceae, Cupressaceae Bartling, Phytolaccaceae, Vitaceae, Nephrolepidaceae, Myrtaceae, Lindsaeaceae, Melastomataceae, Primulaceae | 66.7%, 41%, 37% |
| Extreme ecologically sensitive area | 2–5 (3) | Gramineae (2:2), Rubiaceae (2:2), Rosaceae (1:2) | 10%, 16%, 18% |
| | 1 (27) | Asphodelaceae, Smilacaceae, Primulaceae, Labiatae, Cannabaceae, Leguminosae, Menispermaceae, Pteridaceae, Lygodiaceae, Elaeagnaceae, Apocynaceae, Malvaceae, Compositae, Gleicheniaceae, Vitaceae, Solanaceae, Thymelaeaceae, Umbelliferae, Moraceae, Pinaceae Lindl., Asparagaceae, Celastraceae, Pentaphylacaceae, Salicaceae, Melastomataceae, Rutaceae, Lauraceae | 90%, 84%, 82% |

**Table A2.** Dominant species in plant communities in typical sample sites in the mountains of Pingtan Island.

| Sensitivity Zones | No. | Name of Plant Community | Plant Community |
|---|---|---|---|
| Moderate ecologically sensitive area | J2 | *A. confuse + Litsea rotundifolia—Zanthoxylum nitidum + L. rotundifolia—M. floridulus cluster* | forest |
| | J3 | *A. confusa + Celtis sinensis—L. rotundifolia—Oplismenus undulatifolius cluster* | forest |
| | J6 | *C. equisetifolia—Z. nitidum—O. undulatifolius cluster* | forest |
| | J8 | *S. superba + Cunninghamia lanceolata—S. superba-Adiantum capillus-veneris cluster* | forest |
| | J16 | *P. thunbergii-Dodonaea viscosa—M. floridulus cluster* | forest |
| | N2 | *A. confusa + Casearia glomerata—C. glomerata—Lygodium japonicum cluster* | forest |
| | N3 | *A. confusa +P. thunbergii—M. candidum—Cyclosorus acuminatus cluster* | forest |
| | W3 | *A. confusa—Nerium indicum—Dicranopteris dichotoma cluster* | forest |

**Table A2.** *Cont.*

| Sensitivity Zones | No. | Name of Plant Community | Plant Community |
|---|---|---|---|
| High ecologically sensitive area | J1 | *A. confusa + L. rotundifolia—Ardisia crenata-Nephrolepis auriculata cluster* | forest |
| | J4 | *C. equisetifolia—C. glomerata—O. undulatifolius cluster* | forest |
| | J5 | *C. equisetifolia—L. rotundifolia—Psychotria serpens cluster* | forest |
| | J7 | *P. elliottii—M. candidum—Dianella ensifolia cluster* | forest |
| | J9 | *P. elliottii + C. equisetifolia—C. equisetifolia + L. rotundifolia—D. ensifolia cluster* | forest |
| | J13 | *P. thunbergii—E. emarginata + A. confusa—M. floridulus cluster* | forest |
| | J14 | *A. confusa + M. candidum—Setaria viridis cluster* | scrub |
| | J15 | *A. confusa + L. rotundifolia—L. rotundifolia + A. crenata—D. dichotoma cluster* | forest |
| | N1 | *A. confusa + C. glomerata—C. glomerata-D. dichotoma cluster* | forest |
| | N5 | *P. thunbergii + E. emarginata—D. viscosa—Ischaemum indicum cluster* | forest |
| | N6 | *A. confusa + E. emarginata—D. ensifolia cluster* | scrub |
| | N7 | *C. equisetifolia—E. emarginata—M. floridulus cluster* | forest |
| | W1 | *A. confusa—Xylosma racemosum—D. ensifolia cluster* | forest |
| | W2 | *A. confusa + F. formosana—E. emarginata—A. capillus-veneris cluster* | forest |
| | W3 | *A. confusa—N. indicum—D. dichotoma cluster* | forest |
| | W4 | *P. thunbergia + A. confusa—Artemisia capillaris cluster* | scrub |
| | W5 | *A. confusa + S. superba—Cudrania cochinchinensis—D. ensifolia cluster* | forest |
| | W6 | *A. confusa + S. superba—F. formosana—A. capillus-veneris cluster* | forest |
| | W7 | *A. confusa + F. formosana—C. cochinchinensis—C. acuminatus cluster* | forest |
| | W8 | *E. emarginata + M. candidum—D. ensifolia cluster* | scrub |
| | W9 | *E. emarginata + A. confusa—I. indicum cluster* | scrub |
| | W10 | *A. confusa + E. emarginata—D. ensifolia cluster* | scrub |
| Extreme ecologically sensitive area | J10 | *P. thunbergii + C. sinensis—E. emarginata—O. undulatifolius cluster* | forest |
| | J11 | *P. thunbergii—E. emarginata + M. candidum—D. dichotoma cluster* | forest |
| | J12 | *E. emarginata + A. confusa—M. floridulus cluster* | scrub |

## References


1. Islam, M.A.; Mitra, D.; Dewan, A.; Akhter, S.H. Akhter Coastal multi-hazard vulnerability assessment along the Ganges deltaic coast of Bangladesh—A geospatial approach. *Ocean Coast Manag.* **2016**, *127*, 1–15. [CrossRef]
2. Zheng, W.; Cai, F.; Chen, S.; Zhu, J.; Qi, H.; Zhao, S.; Liu, J. Ecological Suitability of Island Development Based on Ecosystem Services Value, Biocapacity and Ecological Footprint: A Case Study of Pingtan Island, Fujian, China. *Sustainability* **2020**, *12*, 2553. [CrossRef]
3. Cao, W.; Li, R.; Chi, X.; Chen, N.; Chen, J.; Zhang, H.; Zhang, F. Island urbanization and its ecological consequences: A case study in the Zhoushan Island, East China. *Ecol. Indic.* **2017**, *76*, 1–14. [CrossRef]
4. Yuan, C.; Hong-Hua, S.; Jing-Kuan, S.; Zhen, G.; De-Ming, M.A. Evaluation on Island Resources and Environment Carrying Capacity under the Background of Urbanization. *J. Nat. Resour.* **2017**, *32*, 1374–1384.
5. Chen, X.; Li, X.; Eladawy, A.; Sha, J. A multi-dimensional vulnerability assessment of Pingtan Island (China) and Nile Delta (Egypt) using ecological Sensitivity-Resilience-Pressure (SRP) model. *Hum. Ecol. Risk Assess. Int.* **2021**, *27*, 1860–1882. [CrossRef]
6. Chi, Y.; Zhang, Z.; Gao, J.; Xie, Z.; Zhao, M.; Wang, E. Evaluating landscape ecological sensitivity of an estuarine island based on landscape pattern across temporal and spatial scales. *Ecol. Indic.* **2019**, *101*, 221–237. [CrossRef]
7. Wei, G.; Yang, Z.; Liang, C.; Yang, X.; Zhang, S. Urban Lake Scenic Protected Area Zoning Based on Ecological Sensitivity Analysis and Remote Sensing: A Case Study of Chaohu Lake Basin, China. *Sustainability* **2022**, *14*, 13155. [CrossRef]
8. Yuantong, J.; Ye, T.; Shuanning, Z. A study on urban ecosecurity pattern of island city: A case study of Pingtan Island. *Acta Ecol. Sin.* **2018**, *38*, 769–777.
9. Qiu, Y.; He, Y.; Li, M.; Zhu, X. A Generalization of Building Clusters in an Urban Wind Field Simulated by CFD. *Atmosphere* **2024**, *15*, 9. [CrossRef]

10. Gong, D.; Dai, X.; Zhou, L. Satellite-Based Optimization and Planning of Urban Ventilation Corridors for a Healthy Microclimate Environment. *Sustainability* **2023**, *15*, 15653. [CrossRef]
11. Cheng, X.; Zhao, L.; Ge, Y.; Dong, J.; Peng, Y. Full-Scale/Model Test Comparisons to Validate the Traditional Atmospheric Boundary Layer Wind Tunnel Tests: Literature Review and Personal Perspectives. *Appl. Sci.* **2024**, *14*, 782. [CrossRef]
12. Yi, L.; Yi, Z.; Fu-bin, C.; Qiu-Sheng, L. Aerodynamic loads of tapered tall buildings: Insights from wind tunnel test and CFD. *Structures* **2023**, *56*, 104975.
13. Wei, Y.; He, W.; Zhang, S.; Wang, X.; Peng, Y. CFD simulation and optimization of ventilation for the layout of community architecture inspired by fishbone form. *Int. J. Model. Simul. Sci. Comput.* **2023**, *14*. [CrossRef]
14. Xiaoyan, L.; Ting, S.; Hongwei, Z.; Jiafa, S.; Wei, S. Research on ecology restoration of no-resident sea island in Zhoushan City: Case of ecology restoration of Zhoujiayuan stone pit. *Yangtze River* **2020**, *51*, 53–56.
15. Luo, M.; Xiao, L.; Chen, X.; Lin, K.; Liu, B.; He, Z.; Liu, J.; Zheng, S. Invasive Alien Plants and Invasion Risk Assessment on Pingtan Island. *Sustainability* **2022**, *14*, 923. [CrossRef]
16. Zheng, S.; Yu, B. Landsenses pattern design to mitigate gale conditions in the coastal city—A case study of Pingtan, China. *Int. J. Sustain. Dev. World Ecol.* **2016**, *24*, 352–361. [CrossRef]
17. Wen, X.; Ming, Y.; Gao, Y.; Hu, X. Dynamic Monitoring and Analysis of Ecological Quality of Pingtan Comprehensive Experimental Zone, a New Type of Sea Island City, Based on RSEI. *Sustainability* **2020**, *12*, 21. [CrossRef]
18. Xiaofen, L.; Yixiong, H.; Gongfu, Y.; Li, C. Simulation of vegetation landscape in Pingtan Island based on BP neural network model. *Chin. J. Appl. Ecol.* **2011**, *22*, 2098–2104.
19. Shifaw, E.; Sha, J.; Li, X.; Jiali, S.; Bao, Z. Remote sensing and GIS-based analysis of urban dynamics and modelling of its drivers, the case of Pingtan, China. *Environ. Dev. Sustain.* **2018**, *22*, 2159–2186. [CrossRef]
20. ZhiYong, Y. Flora of seed plants in Pingtan Island, Fujian and effects of exotic plants. *Guihaia* **2017**, *37*, 280–293.
21. Liujing, H.; Zengke, Z.; Junming, Z.; Shaojun, H.; Lili, L.; Qi, W.; Chuanyuan, D.; Xingzhao, L. Functional Traits and Evolution Trend of Wild Plants in Continental Island: A Case Study of Pingtan Island. *J. Trop. Subtrop. Bot.* **2017**, *25*, 429–437.
22. Jianzhong, Z.; Sha, J.; Kai, W.; Chuanyuan, D. Analysis on the characteristics of invasive alien plants in the uninhabited islands of Pingtan. *J. Biosaf.* **2023**, *32*, 348–355.
23. Ai, J.; Yang, L.; Liu, Y.; Yu, K.; Liu, J.; Tian, M.H. Dynamic Landscape Fragmentation and the Driving Forces on Haitan Island, China. *Land* **2022**, *11*, 136. [CrossRef]
24. Li, P.; Zhang, C.; Li, W.; Li, Y. Groundwater Vulnerability Assessment of Pingtan Island in Fuzhou City, China, Based on DRASLI-QUE. *J. Hydrol. Eng.* **2020**, *26*, 05020050. [CrossRef]
25. Jin, J.; Ling, Z.; Li, Z.; Zuo, X.; Fan, X.; Huang, Y.; Wang, X.; Wei, C.; Ren, Y.; Qiu, J. Spatiotemporal distribution of sea-island prehistoric dune sites, Holocene sea levels, and aeolian sand activities in Fujian Province, China. *J. Geogr. Sci.* **2022**, *32*, 1157–1176. [CrossRef]
26. Lin, L.; Hao, Z.; Post, C.J.; Mikhailova, E.A.; Yu, K.; Yang, L.; Liu, J. Monitoring Land Cover Change on a Rapidly Urbanizing Island Using Google Earth Engine. *Appl. Sci.* **2020**, *10*, 7336. [CrossRef]
27. Xuezhen, C. Study on Ecological Protection Forest Construction in Pingtan Comprehensive Experimental Zone. *Environ. Sci. Manag.* **2014**, *39*, 152–155.
28. Qiao, Z. The Ecological Benefits Evaluation of Four Main Coastal Shelterbelt Forests in Pingtan. Master's Thesis, Fujian Normal University, Fuzhou, China, 2015.
29. Jihong, X.; Minying, L.; Mei, L.; Chunxiao, W.; Zhifei, Z.; Qingyan, W.; Zhijun, Q.; Zhen, L.; Yingxue, W.; Qingya, D.; et al. Characteristics of Pinus massoniana forest community and species diversity of island in Sandu Gulf, Ningde, Fujian Province. *Acta Ecol. Sin.* **2023**, *43*, 9827–9843.
30. Liu, Y.; Huang, Y.; Wang, Y.; Wang, C.; Xiao, Z.; Shen, S.; Zeng, J.; Deng, C. Characteristics and Species Diversity of Semi-Natural Plant Communities on Langqi Island. *Biology* **2024**, *13*, 11. [CrossRef]
31. He, Y.Q.; Zeng, J.Y.; Chen, G.J.; Xiao, J.H.; Deng, C.Y. Characteristics and species diversity of typical forest community in Dalian Island of Pingtan, Fujian, China. *Chin. J. Appl. Environ. Biol.* **2022**, *28*, 759–769.
32. Huang, H.; Xiao, Y.; Ding, G.; Liao, L.; Yan, C.; Liu, Q.; Gao, Y.; Xie, X. Comprehensive Evaluation of Island Habitat Quality Based on the Invest Model and Terrain Diversity: A Case Study of Haitan Island, China. *Sustainability* **2023**, *15*, 11293. [CrossRef]
33. Yongchang, S. *Vegetation Ecology*, 2nd ed.; Higher Education Press: Beijing, China, 2017; pp. 44–84.
34. Lan, X.; Linting, Z.; Biao, D.; Chuanyuan, D.; Xia, L.; Degang, J.; Yongming, L. Characteristics of main plant communities on uninhabited islands in Bohai Sea, China. *Chin. J. Plant Ecol.* **2024**, *47*, 1–8.
35. GuoHong, W.; JingYun, F.; Ke, G.; ZongQiang, X.; ZhiYao, T.; ZeHao, S.; RenQing, W.; XiangPing, W.; DeLi, W.; Sheng, Q.; et al. Contents and protocols for the classification and description of Vegetation Formations, Alliances and Associations of vegetation of China. *Chin. J. Plant Ecol.* **2020**, *44*, 128–178.
36. Keping, M. Measurement of biotic community diversity I α diversity (Part 1). *Biodivers. Sci.* **1994**, *2*, 162–168.
37. Feng, Y.; Juárez, R.I.N.; Chambers, J.Q. Remote sensing and statistical analysis of the ellects of hurricane Maria on the forests of Puerto Rico. *Remote Sens. Environ.* **2020**, *247*, 111940. [CrossRef]
38. Ottaviani, G.; Keppel, G.; Götzenberger, L.; Harrison, S.; Opedal, Ø.H.; Conti, L.; Liancourt, P.; Klimešová, J.; Silveira, F.A.O.; Jiménez-Alfaro, B.; et al. Linking Plant Functional Ecology to Island Biogeography. *Trends Plant Sci.* **2020**, *25*, 329–339. [CrossRef]

39. Hetherington-Rauth, M.C.; Johnson, M.T.J. Floral Trait Evolution of Angiosperms on Pacific Islands. *Am. Nat.* **2020**, *196*, 87–100. [CrossRef]
40. Meredith, F.L.; Tindall, M.L.; Hemmings, F.A.; Moles, A.T. Prickly pairs: The proportion of spinescent species does not differ between islands and mainlands. *J. Plant Ecol.* **2019**, *12*, 941–948. [CrossRef]
41. Oishi, Y. Factors that shape the elevational patterns of plant diversity in the Yatsugatake Mountains, Japan. *Ecol. Evol.* **2021**, *11*, 4887–4897. [CrossRef]
42. Andoval, J.R.; Ackerman, J.D.; Tremblay, R.L. Island biogeography of native and alien plant species: Contrasting drivers of diversity across the Lesser Antilles. *Divers. Distrib.* **2020**, *26*, 1539–1550.
43. Yu, J.; Shen, L.; Li, D.; Guo, S. Determinants of bryophyte species richness on the Zhoushan Archipelago, China. *Basic Appl. Ecol.* **2019**, *37*, 38–50. [CrossRef]
44. Valli, A.T.; Kougioumoutzis, K.; Iliadou, E.; Panitsa, M.; Trigas, P. Determinants of alpha and beta vascular plant diversity in Mediterranean island systems: The Ionian islands, Greece. *Nord. J. Bot.* **2018**, *37*, e02156. [CrossRef]
45. Irl, S.D.H.; Schweiger, A.H.; Steinbauer, M.J.; Ah Peng, C.; Arévalo, J.R.; Beierkuhnlein, C.; Chiarucci, A.; Daehler, C.C.; Fernández Palacios, J.M.; Flores, O.; et al. Human impact, climate and dispersal strategies determine plant invasion on islands. *J. Biogeogr.* **2021**, *48*, 1889–1903. [CrossRef]
46. Kai, W.; Jianzhong, Z.; Ming, Y.; Yaqin, H.; Xiaojie, S.; Chuanyuan, D. Niche characteristics of dominant species in typical plant communities in Guangyou Island, Pingtan. *J. For. Environ.* **2020**, *40*, 290–297.
47. Hillebrand, H.; Bennett, D.M.; Cadotte, M.W. Consequences of dominance: A review of evenness effects on local and regional ecosystem processes. *Ecology* **2008**, *89*, 1510–1520. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# Evaluation of the Impact of Informal Settlements on the Physical and Mental Health of Residents—Case Study Santa Marta—Bogotá, Colombia

**Camilo Alberto Torres Parra [1], Yelinca Nalena Saldeño Madero [1,*], Mauricio González Méndez [2], Isidoro Fasolino [3], Noé Villegas Flores [4], Michele Grimaldi [3], Natalia Carrillo Acosta [2] and Federica Cicalese [3]**

[1] Civil Engineering Program of the Faculty of Engineering, Universidad Católica de Colombia, Bogotá 11112, Colombia; catorres@ucatolica.edu.co
[2] School of Environmental and Rural Studies, Pontificia Universidad Javeriana, Bogotá 110231, Colombia; gonzalez.alex@javeriana.edu.co (M.G.M.); natalia-carrillo@javeriana.edu.co (N.C.A.)
[3] Department of Civil Engineering, Universidad de Salerno, 84084 Fisciano, Italy; i.fasolino@unisa.it (I.F.); migrimaldi@unisa.it (M.G.); f.cicalese10@studenti.unisa.it (F.C.)
[4] Instituto Latinoamericano de Tecnología, Infraestructura y Territorio, Universidade Federal da Integração Latino-Americana, Foz de Iguazu 85867970, Brazil; noe.flores@unila.edu.br
* Correspondence: ynsaldeno@ucatolica.edu.co; Tel.: +57-3006329933

**Abstract:** The growth of the informal city in Latin America has caused its own dynamics related to urban unsustainability due to the disorderly occupation of the territory. The precarious characteristics of informal neighborhoods have increased the mortality processes in their inhabitants, increasing the poverty and marginality indexes in Latin American urban settlements. This work was developed within the international research project "Modeling informality in Latin America based on indicators of sustainable urban development. Case study Yomasa, Bogotá-Colombia". This work was developed under the mixed research approach which allowed focusing on a nested concurrent design of dominant model (DIAC), which was carried out in the Santa Marta sector of the locality of Ciudad Bolivar, in Bogotá Colombia, with the participation of 20 people from the studied community and supported by 16 students of Civil Engineering of the Catholic University of Colombia. The work resulted in a total of 31 indicators related to neighborhood informality, 17 impacts on the territory, and 8 pathologies, establishing the intrinsic relationship between informality, poverty, and public health of the inhabitant at the urban level.

**Keywords:** urban informality; public health; impact on the territory

**Citation:** Torres Parra, C.A.; Saldeño Madero, Y.N.; González Méndez, M.; Fasolino, I.; Villegas Flores, N.; Grimaldi, M.; Carrillo Acosta, N.; Cicalese, F. Evaluation of the Impact of Informal Settlements on the Physical and Mental Health of Residents—Case Study Santa Marta—Bogotá, Colombia. *Sustainability* **2024**, *16*, 1964. https://doi.org/10.3390/su16051964

Academic Editors: Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Baojie He and Shi Cheng

Received: 6 September 2023
Revised: 9 January 2024
Accepted: 10 January 2024
Published: 27 February 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Urban growth in cities has increased exponentially in recent decades, generating a significant increase in urban informal settlements, especially in Latin American cities, resulting in a high expansion of urban territories in a disorderly manner [1–3]. The city as the central axis of economic development has gradually been transformed into an epicenter saturated with urban inhabitants, industry, transportation, pollution, informality, climate change, citizen insecurity, and urban overcrowding, among others. In this scenario, and especially in view of the reduced foresight and planning of Latin American cities, this has had a negative impact on the use and optimization of the necessary resources that an urban territory should have in order to provide a perception of quality of life for its inhabitants [4,5].

Nearly one billion people live on the continents of Asia, Africa, and Latin America, equivalent to one-sixth of the world's population and one-third of all urban dwellers who live in informal settlements, unplanned environments, and precarious housing. According to UN-Habitat, this number is expected to double by 2030. Approximately 1.3 billion people live below the poverty line, and, of these, 886 million live in middle-income countries such

as Latin America, increasing informal settlements, poverty, and facing risks of polluted air, unhealthy water, and malnutrition [6–9].

There is a perception of an urban crisis in Latin American countries, a pressing trend in loss of quality of life in many cities that materializes in direct risks to their inhabitants as well as to the territories to which they belong culturally and socially [10]. This urban crisis associated with population growth and poverty that converge in underdeveloped cities is characterized by poor planning and informality in urban development [11]. The 2002 United Nations Environment Program Report has stated that poverty is one of the main factors that generate environmental degradation and neighborhood informality and is intrinsically related to accelerated urbanization and globalization. This phenomenon affects, to a certain extent, equitable urban developments, excluding people living in the informal city [12].

Informal neighborhoods in Latin America often have negative impacts on various strategic ecosystems, exceeding their carrying capacity, limiting environmental services, and accelerating climate change [13]. In this context, the inhabitants of informal neighborhoods live in inadequate housing located in high-risk areas (in most cases not mitigable) and in places where public spaces are invaded by illegal groups that sell lots in areas that, due to their geographic location and danger, end up being unsuitable for creating a decent urban space [14]. These types of buildings do not have coverage of basic public services, public transportation, basic urban infrastructure, and clear land legalization processes, accentuating the existing correlation between poverty and public health in a territory [12,15]. The conditions of environmental pollution, exclusion, violence, misery, precarious habitability, high energy, natural resource consumption, unemployment, informal housing, urban overcrowding, low governance, and high migration limit urban growth and magnify poverty, informality, and unhealthiness in Latin American contexts [16,17].

The concept of quality of life from an urban planning perspective is considered as a determinant to conceive a more inclusive and friendly urban design for its inhabitants, so it can be understood as the level of satisfaction they have in cities since it conditions the spatial and territorial planning strategies that are projected in urban areas by the regulatory bodies since it directly affects the social, environmental, economic, cultural and legislative components because the quality of life must consider the systemic relationships between these factors in order to have a positive impact on human beings [18]. This dynamic concept, which goes beyond leisure, increased income, and material goods, also depends on the opportunities that people have to obtain what they consider valuable and that provide them with a feeling of well-being and security in their environment [19].

To determine the level of quality of life of a population from a health perspective, the dimensions of basic infrastructure, housing, household services, environment, and employment must be taken into account. With these needs covered, the biological territorial vulnerability of the inhabitant gradually decreases, which is related to fundamental aspects of public health that mainly affect the informal city. The impacts caused by the increase in biological vulnerability can increase poverty in terms of the presence of diseases and malnutrition, which prevent the inhabitants of the neighborhoods from improving their quality of life conditions, given the need to allocate a greater proportion of their income to corrective health issues [6].

This study, focused on the dynamics of the informal city, was developed in a community attached to the TECHO Colombia Organization, which is made up of volunteers together with inhabitants of informal settlements in Latin America who work to support the overcoming of poverty through training and joint action of its inhabitants, volunteers, and other actors by improving urban habitability with the implementation of community infrastructure projects, education for development, and social entrepreneurship [20].

Therefore, this work sought to address the complexity of unplanned urban spaces from an evaluation of their level of sustainability, taking into account the impacts on the territory and their relationship with the health-disease processes to which their inhabitants are exposed. Many of the measurement processes consulted at the global and local levels

focus on reporting numerical indicators without taking into account the impacts they have on people's quality of life, for which this study focused on public health. Likewise, many of the results presented to the communities are not fully understood because the numerical expressions are not justified in a correlative manner with the reality that many of these populations in Latin America live because they are far from the formal city.

The main limitations of the study were related to the aspects of accessibility to the territory given its geographic location and the lack of formal transportation to the neighborhood; another limitation was citizen insecurity, so the authors had to coordinate the visits previously with the TECHO Colombia Organization in order not to generate a risk in the face of the crime rate. Likewise, another limitation was related to the spaces to carry out the workshops with the community since there is no basic infrastructure. The social mapping sessions were held in a meeting room of the church of the sector on Sundays, due to the fact that another limitation was the community's time, as they work informally from Monday to Saturday.

Finally, for the follow-up of this work, the authors will rely on the infrastructure area of the TECHO Colombia Organization, as this organization promotes the construction of community infrastructure in the sector with which improvements are projected in terms of roads, retaining walls, recovery of public space, community halls, and emergency housing, works that will improve the indicators and their causalities against impacts on the territory and health-disease processes in the inhabitants.

The document is organized as follows. Section 1.1 provides background information, and Section 1.2 presents the local problem. Section 2 describes the methodological framework of research framed in action research, cross-sectional research, and causal correlation design. The results are presented in Section 3. The discussion of the results is in Section 4, and the conclusions of the study are in Section 5.

### *1.1. Background*

The New Urban Agenda was presented at Habitat III in Quito, Ecuador, in 2016. This agenda functions as a driver of the Sustainable Development Goals (SDGs), in particular SDG 11, which deals with how to make cities and human settlements inclusive, safe, resilient, and sustainable, thus improving the quality of life of its inhabitants [15,21–24].

Regarding indicators of sustainable cities, they developed an analysis of indicator-related factors, such as categories and sectors of informal housing [25,26]. Making a synthetic analysis of smart and other sustainable parameters [27], they compiled different tools of sustainable indicators from the University of Toronto, the World Bank, and the World Resources Institute, as well as Eurostat and the World Health Organization [28] establishing a list of 51 indicators for urban sustainability.

The indicators established by UN-Habitat in its proposal "United for Smart Sustainable Cities—U4SSC (2017)" present indicators from the environmental, economic, and sociocultural dimensions. For their part, Ref. [29] have proposed a methodological tool that allows the analysis of the development of emerging cities with high population density, including factors associated with sustainability, building conditions, and urban renewal. Thus, the Inter-American Development Bank (IDB) has proposed a methodological guide of sustainable development indicators for an emerging city. These indicators are divided into three dimensions: environment, urban and fiscal development, and governance [30].

With regard to different indicators that evaluate neighborhood informality, in the neighborhoods called "Exposición and São Pelegrino", in the city of Caxias do Sul, Brazil, several indicators of housing density, population density, public transportation, as well as parameters of location of parks and squares, equipment, connectivity, and sustainability, have been taken into account. As for the work of analysis at the neighborhood scale in the city of Temuco, Chile [31], in which four neighborhoods have been evaluated using as a basis the system of urban indicators of the Malaga protocol [32], whose methodology is based on the existing distance from a given service to meet a need of an inhabitant. On the other hand, Ref. [18] compared eight informal neighborhoods in the city of Bogotá,

prioritizing indicators related to pedestrian streets, compact and connected development, and mixed land use.

Taking into account that documents were reviewed that presented sustainability indicators from the economic, environmental, and social dimensions, it was identified for this research that the sustainability of a territory is divided into three large areas: the biotic, abiotic, and anthropic parts; having a balance in these dimensions, a territory in addition to being sustainable, is efficient and provides quality of life to its inhabitants. This assertion was fundamental to subsequently define the variables and indicators used in this study together with the community.

*1.2. Problem*

In Bogotá' s specific case, a poverty rate close to 27% was reached in the year of 2019 and showing an increase in the year 2020 of 12.9 percentage points. Likewise, in the year 2021, a Gini coefficient of 0.528 was reached. In this context, there was a setback in the goals corresponding to the mortality rate in children under 5 years of age due to acute malnutrition, more than half of the infant deaths (56%), concentrated especially in the localities of Ciudad Bolivar, Suba, Bosa, Kennedy, and Engativá. In short, in housing, in the context of the year 2021, the qualitative deficit was 9.0% and in quantitative character with a value close to 1.6% [33].

Regarding citizen security in Bogota, in 2021, the homicide rate increased from 13.4 in 2020 to 14.4 in 2021; between 2020 and 2021, the personal injury rate increased by 24.6%; andm in the case of theft from persons in 2021, an increase of 28.6% was observed. Regarding air quality, in the period from 2017 to 2021, the concentration of particulate matter (PM10) in the atmosphere exceeded the permissible limits recommended by the World Health Organization (20 $\mu g/m^3$) due to the increase in freight transportation and in a smaller area planted with trees per inhabitant. By 2021, the amount of waste disposed of in the Doña Juana landfill increased, and only 33.5% of this waste was used. This situation deepened inequality throughout the city, affecting the most vulnerable populations, impacting their quality of life in the city [33].

As for the informal neighborhood areas of Ciudad Bolívar, the residential areas are close to places such as garbage dumps and areas of natural risk. Coverage of public utilities is precarious in terms of water, sewage, garbage collection, and natural gas. The locality has air pollution with measurements of more than 20 $\mu g/m^3$ (in PM10), noise problems, excessive advertising, and environmental unhealthiness. In this scenario, about 34% of the inhabitants stated that this type of pollution is frequently present in the surroundings of their homes, affecting the well-being of the family. In a demographic context, there is an active population of 361,000 people, 80% of whom work in the informal sector. At a general level, the percentage of people in multidimensional poverty is one of the highest in Bogota, with 97,447 people with unsatisfied basic needs (UBN), and the displaced population living in this locality is significantly high, with values close to 70% [34].

On the other hand, community processes of sustainable, legal, and formal occupation of a territory are dynamic agents in the planning of cities that promote the care of their ecosystems and, above all, that respect institutionalism and promote social development, conditions that show little progress in Latin America [35]. Population growth in urban areas is expected to continue at a dizzying pace in the coming decades, which has significant implications for environmental sustainability and public health in the territories [36]. However, urbanization is not only a spatial process promoted by population growth but also a stimulus that, if properly oriented, can be used to overcome other global problems such as poverty, inequality, environmental degradation, climate change, biodiversity loss, and conflicts, which are critical elements of the 2030 Agenda and are related to quality of life [30].

The territory of Santa Marta is an informal settlement located on the border between Ciudad Bolívar in Bogotá and the Progreso neighborhood in the municipality of Soacha, Cundinamarca. The informal occupation of this sector began in the 1990s due to the

displacement of people from rural areas of Colombia as a result of violence. This situation of displacement, which continues to grow exponentially at present, has increased problems in the neighborhood, such as a lack of formal public services, air pollution problems, soil and nearby water sources, lack of green areas, open dumps, the presence of pests and vectors, teenage pregnancy, citizen insecurity, poor conditions of primary and secondary roads, poor condition of pedestrian paths, high probability of natural emergencies, and insecurity in the tenure and self-construction of housing, among others. This situation has had a negative impact on the quality of life of the sector's inhabitants, exposing them to a high probability of presenting episodes of physical and mental illnesses as a result of the neighborhood's informality (Figure 1).

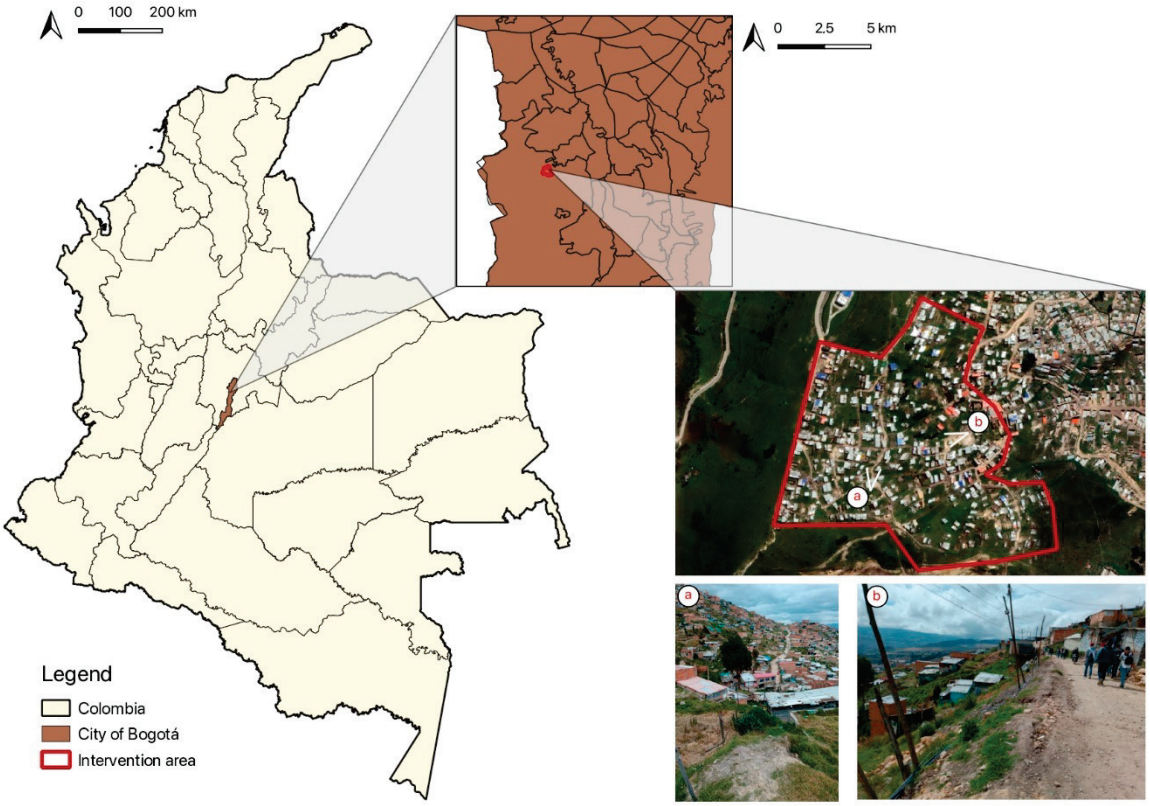



**Figure 1.** Geospatial location of the Santa Marta neighborhood. (**a**) upper part of the territory; (**b**) the main road (source: elaboration by the authors).

## 2. Materials and Methods

To develop this work, mixed research was chosen to meet the proposed objectives, which allowed focusing on a nested or embedded concurrent dominant model design (DIAC), which simultaneously collects quantitative and qualitative data, and where a predominant method guides the scope of the project and the fulfillment of the objectives. Likewise, one approach can be framed within the other method, with the lower priority method being nested or embedded within the one that is considered central [37].

For the purposes of the research, the central method was framed in the action-research design related to qualitative research. Its main purpose is focused on providing information to guide decision-making in the communities, promoting social change, contributing to the transformation of reality, and making people aware of their role in the process of appropriation of their territory. The three main phases of action research designs are: to observe, where the problem is visualized, and data are collected; the thinking phase, where the data obtained are analyzed and interpreted; and, finally, the acting phase, where the findings are presented to the community in order to promote solutions adjusted to the contexts where the first two phases were developed [37].

The process to carry out this research variant was followed in the study in order to fulfill the objectives of: to establish participatively dependent and independent variables and to define indicators related to neighborhood informality, for which the study was conducted with the community. The variables and indicators were selected based on the identification of their needs in relation to the territory in a participatory work of social mapping, in addition to having as a basis for the exercise the antecedents related in this document.

Based on the action research approach, the phases of the methodology were developed as follows (Figure 2):

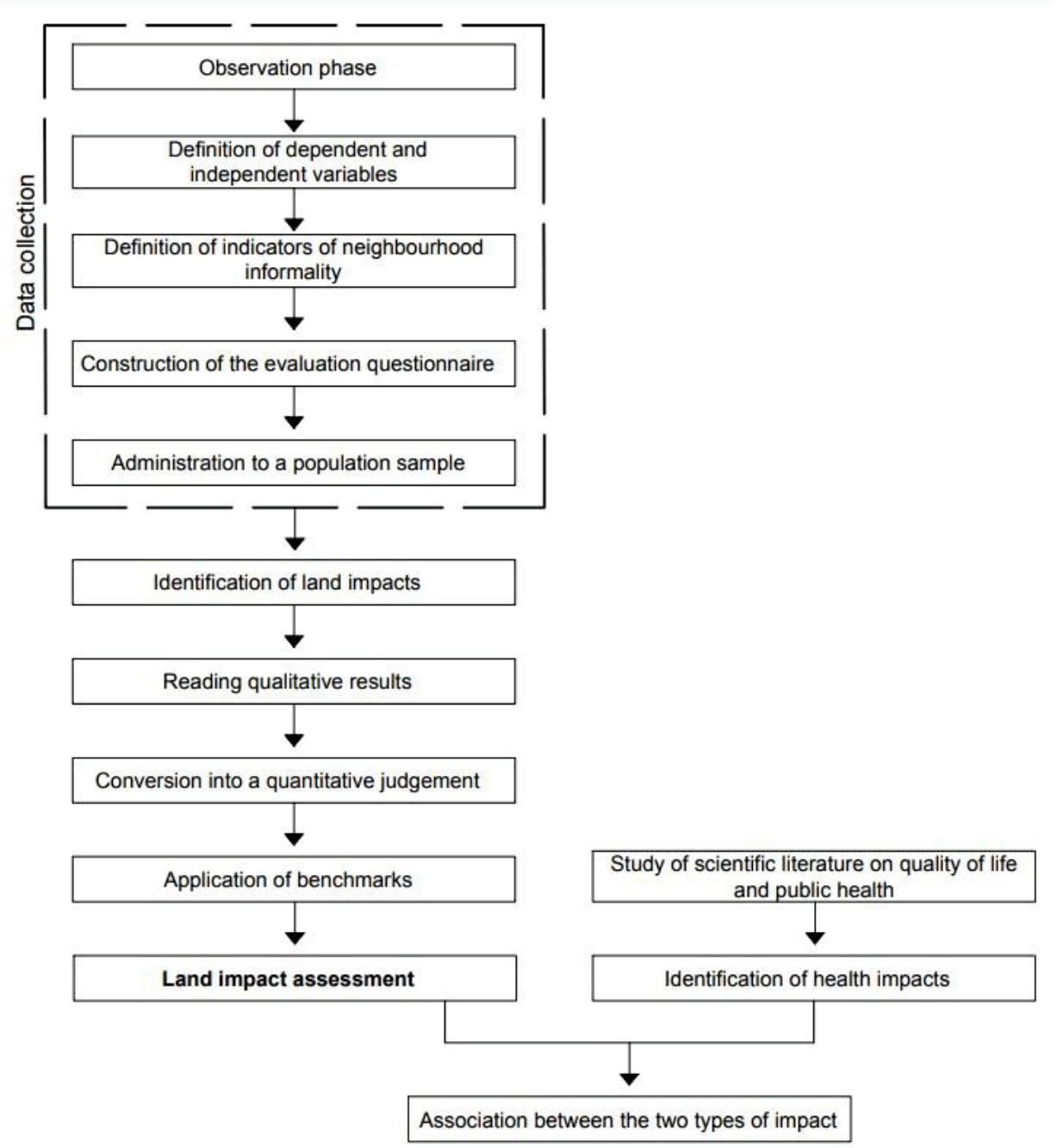



**Figure 2.** Methodology flow diagram (source: elaboration by the authors).

Phase 1—Construction of the database (to be observed)

1.1. Selection of the neighborhood considered

The sampling implemented in the area of Santa Marta in Ciudad Bolivar was related to quantitative research, as the territory and a number of individuals were selected for the study, taking into account that they should be linked to the work developed in the neighborhood by the TECHO Colombia Organization, an organization that has an agreement with the Catholic University of Colombia to develop classroom work, research, and social projection aimed at overcoming poverty in informal contexts. For this specific case, we first proposed the definition of the unit of analysis, which focused on 20 people participating in the processes carried out by the infrastructure area of TECHO Colombia in the sector because they have been trained in environmental education, community infrastructure, and social entrepreneurship by the organization's staff, which facilitated the work with the team proposing this research.

Taking into account the above, it was decided to delimit the unit of analysis to these participants since they know in depth the problems of habitability to which their relatives and neighbors are exposed, and they are also aware of the real situation of the territory. Therefore, a non-probabilistic sampling was carried out, where the choice of the elements did not depend on probability but on the causes related to the characteristics of the research and the interest of the researcher [37], which is why, in these 20 people, the element of representativeness of the population necessary for the proposed research was found, as this small portion of the community of Santa Marta had the availability to attend the work sessions, confidence in the processes developed by the TECHO Colombia Organization, and recognition by the neighbors of the neighborhood as community leaders.

Likewise, 16 ninth-semester civil engineering students from the Community Development Project course participated, who supported the processes of collecting information in the field, developing the community work sessions and reporting data to the research team. It should be noted that the linkage of this group of students was carried out through a classroom project that was carried out since 2017 with the TECHO Colombia Organization, in which, every six months, students are linked to a volunteer program that promotes the design and construction of community infrastructure in informal territories attached to the TECHO Colombia Organization.

### 1.2. Construction of the evaluation questionnaire

In order to conduct an analysis of the context of informality of the community of Santa Marta with respect to their conditions of occupation and sustainability, it was necessary to identify the units of analysis focused on the dependent and independent variables and indicators. Regarding the selected variables, these were identified together with the students and the participating community in a tour that was carried out in 4 evenly distributed groups (students and people from the community) accompanied by two professors from the Catholic University of Colombia of the Civil Engineering program.

During this tour, it became evident first hand that the problems observed by the team and those expressed verbally by the community should be categorized into two types of variables; dependent variables are those that are studied and measured based on the manipulation or variation in independent variables, which are those that have a direct effect on the dependent variable [37]. Therefore, for the development of this day of recognition and categorization of the dependent and independent variables, the work team relied on the methodology of [38], which aimed to collect data in the field presenting a series of variables and indicators organized in such a way that the territories could be categorized at the urban level considering three degrees of evaluation: precarious, consolidated, and semi-consolidated [38].

Based on the above, the dependent and independent variables that were considered precarious during the field visit were taken into account for this study since, based on what was collected during the day by the students and what was expressed by the community, the variables that required priority attention to improve the informal conditions of the sector were:

1. Basic services: formal and informal infrastructure works arranged in a territory to meet the needs of the population in terms of public services at the urban level.

1.1. Drinking water: water with disinfection processes suitable for human consumption and food preparation.
1.2. Sanitation services: conventional or alternative system for the treatment and disposal of excreta at the household level.
1.3. Cleaning services: storage, collection, and final disposal of household, commercial, municipal, hazardous, and debris solid waste.
1.4. Energy: energy infrastructure and other fuel sources with formal or informal connection at the household level.
1.5. Mobility: set of services and infrastructure that facilitate movement from one place to another by different means, whether motorized, non-motorized, or animal traction.

2. The uses of the peri-domicile: delimited urban environment, its resources, services, equipment, and neighborhood.
   2.1. Land uses: distribution of land uses in a territory established by land use plans.
   2.2. Public spaces: directly related to common goods where the ownership of these is not subordinated to a particular holder.
3. Risks on the ground: identification of areas with mass removal and flooding processes that affect security of tenure in a territory.
   3.1. Natural factors: set of risks present in a territory that may lead to flooding and mass removal effects.
4. Housing tenure: legally and socially defined perception that validates the recognition and possession of private property.
   4.1. Illegality: absence of an institutional recognition validated in administrative acts to corroborate the legality of housing units.
   4.2. Construction materials: raw materials and set of techniques protected by current legislation to build infrastructure works designed to improve the shelter of human beings.
   4.3. Sustainable systems: alternative systems of utilization at the household level.
5. Socioeconomic: social, cultural, and age characteristics linked to the person and defined by the territory and environment in which he/she develops.
   5.1. Social mix: denotes the social diversity of a delimited territory.
   5.2. Vulnerable population: population under 5 years of age and over 60 years of age.

Phase 2—Evaluation of the impact on the territory (thinking)

To comply with the DIAC design, the nested approach to quantitative research relied on a trans-sectional or cross-sectional research design approach, which is based on data collection in a single moment at a single time. The purpose of this is to identify situations and analyze their incidence at a given time, which is why the single data collection may cover several groups or subgroups of people in the community, situations, or events [37,39].

Therefore, after identifying and defining the dependent and independent variables, the indicators to be evaluated were proposed during another day of field work with the same groups of students and community. The 31 proposed indicators were designed in two workshops in the subject of the Community Development Project, where, with the groups of students, the means of verification in the field were constructed and defined to categorize the territory in what was considered a precarious territory, which, according to [38], is characterized by its high conditions of informality in its occupation, and the availability, access, and quality are difficult for its inhabitants in terms of: open physical spaces, permanent and temporary lodging, commerce, endowment use, recreation and sports, cultural, furniture, mobility, and comfort.

Having defined the indicators and their means of verification in the field, a second day of work was planned, for which, in the same groups formed, the indicators were

applied, establishing a dynamic of direct and fluid communication between the community and the students. On this day, it was possible to identify that the indicators evaluated in the territory had a series of consequences according to the perception of the inhabitants, as, in the work groups, they stated that garbage; atmospheric pollution; the presence of rats, flies, and sick animals; accidents; insecurity; and lack of public services and urban furniture, among others, were caused by the precariousness of the neighborhood due to its informality in its urban consolidation.

Based on what was evidenced during the field work, in order to facilitate the identification of the relationships between the indicators and the consequences that the community expressed that directly affected their quality of life, causal diagrams (CDs) were used to identify the causal relationships between the different factors and events found in the territory. The CDs were dynamic, which means that they were updated as more information was obtained or changes were made to the system. This allowed teams to update and adjust their models as they learned more about the system in question [40].

Therefore, in order to create the CDs by the group of researchers, they began with the identification of the factors that were contributing to the problem or situation being studied, in this case, how the community's manifestations in the application of the indicators affected their quality of life from the informality of the territory. These factors were represented in the diagram as nodes or boxes. Then, the causal relationships between these factors were identified and represented as arrows connecting the nodes; the arrows indicate the direction of the causal correlation between two nodes. At these nodes, the type of causality that exists within both variables can be placed, being negative (inversely proportional) or positive (directly proportional). This facilitated the understanding of the behavior of the variables and, at the same time, the behavior of the system, which made it easier for the work team to classify the nuisances referred to by the community into impacts that were later discussed with the participating community [41,42].

Taking into account the causalities found, a third working day was planned to validate the impacts caused by the indicators evaluated in the field in a participatory manner. On this day, first-hand information was gathered, where the view of the inhabitants of the sector in relation to the territory was able to identify 17 impacts linked to the daily anthropic activities in the urban area that directly affected the quality of life of the population since a general dissatisfaction of the community was expressed in relation to the following impacts [43–45]:

1. Accidents;
2. Rental of sanitary facilities;
3. Slum construction;
4. Landscape degradation;
5. Water pollution;
6. Excreta contamination;
7. Sewage contamination;
8. Structural vulnerability;
9. Fires;
10. Tenure insecurity;
11. Citizen insecurity;
12. Leachate;
13. Air pollution (particulate matter);
14. Vectors and pests;
15. Hazardous waste;
16. Solid waste;
17. Dumping.

The related impacts were categorized with the help of the students and the tutoring of the teachers to organize the ideas expressed by the population, for which they were supported by a social mapping, where the participants related the indicators with the inconveniences they generated, which served to facilitate the categorization.

Using visual techniques such as problem maps to graphically represent the relationships between different aspects of the environment and to point out problem areas, served for the community to communicate their felt needs with the environment, the need was created to share their views with students and teachers to achieve success in the work process, so that, in this part, thanks to the participation of the community, the local knowledge of the participants and the technical knowledge of the universities was integrated [46,47].

### *2.1. Standardization of Qualitative Judgments*

After identifying the relationship between the indicators and the impacts they had on the inhabitants, we proceeded to quantify the level of these impacts in the territory, as, from the inhabitant's perception, there was no clarity on the degree of affectation of the impacts manifested in the community and their incidence on the quality of life; therefore, we proceeded to review specific bibliography [48–56] to evaluate the impacts caused by human activities, adopting an "ad hoc" qualification method based on the formula proposed by [57,58], where, based on the evaluation of biotic, abiotic, and anthropic indicators, the level of impact on a territory, ecosystem, or sector is reported from an environmental perspective, which is directly related to the concept of quality of life from Sustainable Development Goal 3: Ensure healthy lives and promote well-being for all at all ages from considering that a healthy environment is vital to ensure healthy lives and promote well-being for all at all ages.

In order to apply the formula by the authors in the assigned scale of values, it was necessary to carry out a fourth day of field work, which made it possible to identify, in a participatory manner, the existence, speed, importance, and permanence of each impact reported in the territory by the participants. With the above exercise, it was possible to quantify the perception of the inhabitant and thus identify the level of the impacts found in the application of the indicators in the territory.

### *2.2. Value of the Level of Impacts*

The following mathematical formula was used to determine the value of the level of impacts [57,58]:

$$\text{Impact level value} = E(C \times V \times I) + (C \times P).$$

where each of the variables in the formula is described below (Table 1):

**Table 1.** Impact level assessment variables.

| **Existence (E): The certainty or probability that the impact will materialize in the territory.** | | |
|---|---|---|
| **Rank** | **Valuation** | |
| Certain | 1 | |
| Very likely | 0.7–0.9 | |
| Likely | 0.4–0.6 | |
| Unlikely | 0.1–0.3 | |
| **Velocity (V): The time in months in which the impact on the territory occurs.** | | |
| **Rank** | **Velocity in Months** | **Rating** |
| Very fast | Less than 1 | 0.9–1 |
| Rapid | 1–5 | 0.7–0.8 |
| Medium | 6–12 | 0.5–0.6 |
| Slow | 13–24 | 0.3–0.4 |
| Very Slow | Greater than 24 | 0.1–0.2 |

**Table 1.** *Cont.*

| **Importance (I): The magnitude of the impact on the territory.** | | |
|---|---|---|
| **Rank** | **Dimension (%)** | **Rating** |
| Very high | 80–100 | 9–10 |
| High | 60–79 | 7–8 |
| Medium | 40–59 | 5–6 |
| Low | 20–39 | 3–4 |
| Very Slow | 0–19 | 1–2 |
| **Permanence (P): The duration in years of the impact on the territory.** | | |
| **Rank** | **Duration in Years** | **Rating** |
| Very long | Greater than 10 | 10 |
| Long | 7–10 | 7–9 |
| Medium | 4–6 | 4–6 |
| Short | 1–3 | 1 |
| Very Short | Less than 1 | 0.1–0.9 |

Weight Balance Constant (C): 0.5

Taking into account the ranges and valuations of the variables described in the formula, we proceeded to determine the quantitative value of the impacts identified in the territory, taking into account the following categorization (Table 2):

**Table 2.** Territory Impact Level.

| **Territory Impact Level** | |
|---|---|
| **Rank** | **Impact Level Value** |
| Very high | 8.1–10 |
| High | 6.1–8 |
| Medium | 4.1–6 |
| Low | 2.1–4 |
| Very Slow | 0–2 |

From the application of the mathematical formula, the assessment of the level of impacts was obtained.

Phase 3—Impact on the health of the inhabitant (act)

### 3.1. Definition of health impacts

Taking into account the previous quantitative hierarchy presenting the range and valuation of the level of impacts on the territory, in order to establish the relationship between an informal precarious territory and the direct consequences of this on the quality of life of the inhabitant, it was necessary to relate how the impacts could affect the inhabitant from the public health aspect. To each impact, health-disease episodes were related according to the provisions of the Faculty of Medicine of the National University of Colombia, which developed a transectional methodology in which the major risk factors that link physical and mental diseases with housing and environmental indicators are coded, with the objective of dimensioning a base epidemiological scenario in a territory [59,60].

To develop this correlation between impacts on the territory and physical and mental illnesses, the research developed by [59] was reviewed. The physical and mental health episodes that occur in an urban settlement are related if the following conditions are not taken into account: comfort in housing, sufficient and separate spaces in housing,

structurally safe housing, housing materials, security of tenure, access to public services, basic sanitation, storage and handling of water for human consumption, vectors, pests and sick animals, urban equipment, unsafe land, accidents, exposure to contamination, community participation, preventive health, diseases, and poverty.

After making this correlation, we proceeded to corroborate the morbidity and mortality episodes in the locality of Ciudad Bolivar in Bogotá, whose data were reviewed in [61], which interprets individual, family and community health as the result of biological and psychological influences of a person's immediate physical and social environment. This text provided a diagnosis of the quality of life, health and disease conditions of the population of Ciudad Bolivar in general, which, based on statistical, geographic and epidemiological data, facilitated the identification of patterns, variables and different social and population phenomena that affect health and disease processes in the community.

### 3.2. Association between impact on the territory and health impact

Based on the information consulted, the number of impacts susceptible to materialize a disease was determined. In a fifth day of community work, the team of students presented the proposal of correlation between the categorized impacts and the health and disease processes they entailed, for which it was verified with the population that the pathologies did occur in the community, making the participants associate that the conditions of informality could be the cause of a high probability of the physical and mental diseases they had been diagnosed with or perceived, directly affecting their quality of life.

With regard to the thinking phase corresponding to data analysis, it was important to take into account the points of view of those directly affected and of the actors who intend to contribute to the generation of knowledge in the territory. Therefore, it was essential to involve the following actors: the community, the TECHO Colombia organization, researchers, and students; from work processes, it would be possible to understand the direct relationship between neighborhood informality and public health in the inhabitant, as without actively involving the community, it is unlikely to generate a long-term sustainable solution, reducing the group's effort to little more than good intentions and paternalism [62].

## 3. Results

The methodological framework made it possible to participatively establish 5 dependent variables and 13 independent variables, define 31 indicators, identify 17 impacts present in the territory, and determine a correlation between indicators and impacts linked to neighborhood informality, in order to relate 8 pathologies that directly affect the quality of life and well-being of the population from the health-disease processes linked to the territory of Santa Marta.

According to Tables 3 and 4, it was established that the neighborhood is made up of 200 households, where one third of the population living in the territory is of Afro descendant and an indigenous origin. Due to the displacement of inhabitants from rural areas to urban peripheries, the total population is made up of displaced persons from different regions of the country, where approximately 10% of the people in the sector are adults over 60 years of age, and 20% of them are children under 5 years of age.

Regarding the basic services variable, the 200 families living in the neighborhood are supplied with illegal connections to access drinking water, using handmade connections made with polyethylene hoses and PVC fittings; this supply is illegally connected to a mother pipe of the Bogota aqueduct. There is no formalized sewage service; excreta are disposed of in open-air ditches that are gravity-fed to an environmental protection zone, and some houses rent sanitation services from their neighbors. Solid waste and debris are disposed of in three specific locations: in the Terreros wetland, along the main roads, and in the community park; although garbage collection is provided every other day, it is difficult to access because of the narrow, poorly maintained roads. The area lacks gas service, pedestrian walkways, bike paths, and bus stops. Energy connections are illegal and

are supported by wooden poles, and the roads are in poor condition with a high presence of particulate matter.

Regarding peri-domicile uses, in relation to land uses, two commercial zones were identified, one in the upper zone and the other in the lower part of the sector, where the main roads are located; these zones offer basic family products and cleaning supplies, as well as taverns. The neighborhood only has two churches and a school; the other services are not covered, so the indicators are negative, and the inhabitants must move to other sectors of the city to meet these needs. In the residential area, ten blocks were identified where all the houses are of informal origin, and, on average, each house is 5 to 5.5 m wide. Also, in terms of public spaces, there is only one environmental protection area, the Terreros wetland on the border with the municipality of Soacha Cundinamarca, but it is contaminated by sewage discharges; apart from the wetland, there is an area with vegetation cover, a communal park in poor condition with the presence of solid waste, hazardous waste (dead animals), and debris, which serves as a place for meeting, recreation, sports practice, and consumption of psychoactive substances.

**Table 3.** Indicators of neighborhood informality.

| Dependent Variable | Independent Variable | Indicator |
|---|---|---|
| Basic services | Drinking water | Average number of formal access points to drinking water |
| | | Average number of informal access points to drinking water |
| | Sanitary service | Average number of formal access points to sanitary services |
| | | Average number of informal access points to sanitary services |
| | Sanitation services | Average number of informal points for solid waste disposal |
| | | Average number of informal points for debris disposal |
| | Energy | Average number of formal access points to electricity service |
| | | Average number of formal access points to natural gas service |
| | | Average number of points without access to electricity service |
| | Mobility | Average pedestrian spaces |
| | | Average informal transport service stops |
| | | Average bicycle lanes |
| | | Average bicycle lanes |
| Peridomicile use | Land use | Average commercial zones |
| | | Average institutional use zones |
| | | Average residential use zones |
| | Public spaces | Average areas of environmental reserve |
| | | Average public areas with vegetation coverage |
| | | Average parks, squares, and plazas |
| | | Average vandalized public spaces |
| Terrain risks | Natural factors | Average localized mass removal processes |
| | | Average localized floods |
| Housing tenure | Illegality | Average illegal houses per delimited territory |
| | Construction materials | Average houses with damaged floors, walls, and/or roofs |
| | Sustainable systems | Average green roofs |
| | | Average rainwater harvesting and utilization systems |
| | | Average composting points |
| | | Average urban gardens |
| Socioeconomic | Social mix | Average ethnic groups |
| | Vulnerable population | Average adults aged 60 years old |
| | | Average children under 5 years old |

**Table 4.** Results of neighborhood informality indicators.

| No. | Indicator | Formula | Result |
|---|---|---|---|
| 1 | Average formal access points to potable water | # of formal access points to potable water/delimited territory | 0 |
| 2 | Average informal access points to potable water | # of informal access points to potable water/delimited territory | 180 |
| 3 | Average formal access points to sanitation services | # of formal access points to sanitation services/delimited territory | 0 |
| 4 | Average informal access points to sanitation services | # of informal access points to sanitation services/delimited territory | 180 |
| 5 | Average informal points of solid waste disposal | # of informal points of solid waste disposal/delimited territory | 3 |
| 6 | Average informal points of debris disposal | # of informal points of debris disposal/delimited territory | 1 |
| 7 | Average formal access points to electricity service | # of formal access points to electricity service/delimited territory | 0 |
| 8 | Average formal access points to natural gas service | # of formal access points to natural gas service/delimited territory | 0 |
| 9 | Average points without access to electricity service | # of points without access to electricity service/delimited territory | 0 |
| 10 | Average pedestrian spaces | # of pedestrian spaces/delimited territory | 0 |
| 11 | Average informal stops of transportation service | # of informal stops of transportation service/delimited territory | 0 |
| 12 | Average bike lanes | # of bike lanes/delimited territory | 0 |
| 13 | Average stretches of road in poor condition | # of stretches of road in poor condition/delimited territory | 23 |
| 14 | Average commercial use areas | # of commercial use areas/delimited territory | 2 |
| 15 | Average institutional use areas | # of institutional use areas/delimited territory | 3 |
| 16 | Average residential use areas | # of residential use areas/delimited territory | 10 |
| 17 | Average environmental reserve areas | # of environmental reserve areas | 1 |
| 18 | Average public areas with vegetation cover | # of public areas with garden, lawn, or pasture/delimited territory | 1 |
| 19 | Average parks, squares, and plazas | # of parks, squares, and plazas/delimited territory | 1 |
| 20 | Average vandalized public spaces | # of vandalized public spaces/delimited territory | 0 |
| 21 | Average localized mass removal processes | # of localized mass removal processes/delimited territory | 2 |
| 22 | Average localized floods | # of localized floods/delimited territory | 3 |
| 23 | Average illegal dwellings per delimited territory | # of illegal dwellings/delimited territory | 180 |
| 24 | Average dwellings with floors, walls, and/or roofs in poor condition | # of dwellings with floors, walls, and/or roofs in poor condition/delimited territory | 180 |
| 25 | Average green roofs | # of green roofs/delimited territory | 0 |
| 26 | Average rainwater harvesting and utilization systems | # of rainwater harvesting and reuse systems/delimited territory | 0 |
| 27 | Average points with composting | # of points with composting/delimited territory | 0 |
| 28 | Average urban gardens | # of urban gardens/delimited territory | 0 |
| 29 | Average ethnic groups | # of ethnic groups/delimited territory | 2 |
| 30 | Average elderly population | # of elderly population/delimited territory | 80 |
| 31 | Average children under 5 years | # of children under 5 years/delimited territory | 170 |

Regarding the variable of risks in the terrain, it was found that the natural factors of granular material detachment are present in the two main roads of the sector, perceiving a high risk on the part of the community during the rainy season since the runoff drags material from the soil in an approximate of 15 cm per year. There are also three areas with localized flooding due to the lack of mixed sewage systems and the use of artisanal sewage collection networks, which intensifies flooding episodes during the winter season.

Regarding housing tenure, in terms of legality, it was found that the territory is made up of informal dwellings since the people who live there do not have legal documentation accrediting them as owners of the land and buildings. All the houses are self-built and have between 1, 2, and 3 levels; the construction materials used for walls, floors, and roofs are in gray work, in poor condition, or in slum conditions. According to an estimate of the 180 houses identified, 80 are built with masonry and 100 with waste materials such as plastic, metal, and cardboard. No practices that promote the sustainable use of resources, such as rainwater harvesting systems, green roofs, or urban crops, were observed in the houses.

Taking into account the situational framework provided by the application of the indicators, a causal diagram was made (Figure 3) that represents in a systemic way what was expressed by the community in relation to how living in an informal territory affects their quality of life based on the quantitative data collected in the field by the work team.

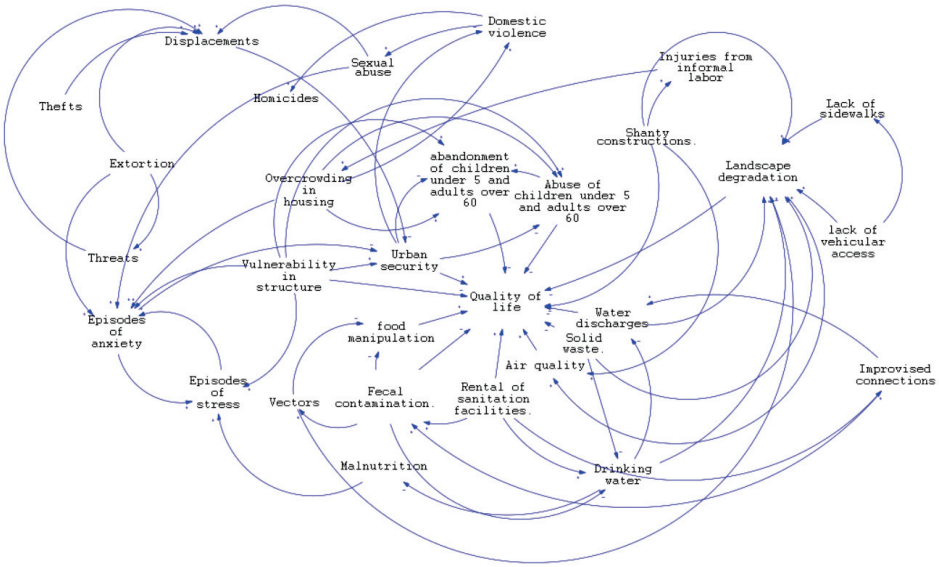



**Figure 3.** Causal diagram between impacts on the territory and quality of life (source: elaboration by the authors).

These causal correlations provided a dynamic and complex system in which it was possible to build a holistic scenario that facilitated the understanding of the impacts caused by the proposed indicators, making it possible to identify the impacts to be evaluated quantitatively in conjunction with the community (Table 5).

Taking into account the above assessment, physical and mental health episodes were identified, which, due to the conditions of neighborhood informality, exposed the community of the Santa Marta sector from the impacts assessed in the territory (Table 6).

**Table 5.** Assessment of the level of impacts on the territory.

| Range | Impact | Impact Level Assessment |
|---|---|---|
| Very high | Water discharges | 10 |
| | Landscape degradation | 10 |
| | Fecal contamination | 10 |
| | Contamination due to standing water | 10 |
| | Water pollution | 9 |
| | Solid waste | 9 |
| | Urban security | 8.5 |
| | Lixiviados | 8.5 |
| | Air quality | 8.5 |
| | Vectors and pests | 8.5 |
| High | Shanty constructions | 8 |
| | Vulnerability in structure | 8 |
| | Accident rate | 8 |
| Medium | Tenure insecurity | 6 |
| | Hazardous waste | 6 |
| Low | Rental lof sanitation facilities | 4 |
| | Fires | 4 |

**Table 6.** Relationship between impacts and pathologies in the territory.

| Pathology | Diseases | Number of Impacts Causing Disease |
|---|---|---|
| Respiratory diseases | Bronchiolitis, bronchitis, pneumonia, rhinitis, asthma, tuberculosis, meningococcal disease, and COPD. | 12 |
| Mental illnesses | Depression, insecurity, stress, neurosis, violence, alcoholism, and drug addiction. | 10 |
| Gastroenterogenic diseases | Gastrointestinal infections, food poisoning, intestinal parasitosis, typhoid fever, diarrhea, cholera, and leptospirosis. | 11 |
| Vector and pest diseases | Filariasis, toxoplasmosis, rabies, plague, Chagas disease, schistosomiasis, geohelminthiasis, typhoid, and typhoid. | 9 |
| Skin infections | Ringworm, candidiasis, athlete's foot, herpes, scabies, pediculosis, and insect bites. | 7 |
| Cardiovascular diseases | Heart failure, arterial hypertension or high blood pressure, excess cholesterol, myocardial infarction, angina pectoris, and heart rhythm disorders. | 4 |
| Accidents | Trauma, poisoning, asphyxiation, explosions, burns, injury, fracture, contusion, run over, and sprain. | 3 |
| Crimes | Robbery, threats, extortion, sexual crimes, personal injuries, domestic violence, and homicides. | 2 |

## 4. Discussion

Taking into account the results obtained, it was inferred that the majority of children under 5 years of age suffer from moderate malnutrition and are susceptible to morbidities such as Acute Respiratory Infections (ARI) due to factors such as low family income, parents with low educational level, overcrowding and inadequate ventilation in the homes, lack of housing, and unsatisfied basic needs. Other factors identified in this situation are climate variability and environmental contamination, especially the impact on air quality related to particulate matter due to poor road conditions in the territory. On the other hand, factors such as overcrowding and housing conditions, where several household members must share the same room or there is a need to leave children in the care of other family members, may have an impact on the occurrence of sexual abuse and domestic violence.

It is also argued that in relation to the 60 year old adult, this focal group requires permanent help to carry out the activities of daily life; in addition, they are exposed to factors such as domestic violence, especially abandonment, as they do not have the basic needs of housing, employment, and public services covered, requiring them to go out to work despite their advanced age and depend on subsidies or contributions made by children, relatives, or, sometimes, neighbors or foundations. They are generally exposed to risk factors such as accidents, respiratory diseases, gastroenterogenic diseases, skin infections, mental illnesses, and psychoactive substance use. With regard to cardiovascular diseases, the community reported that high blood pressure is common in people over 60 years of age, either due to poor access to public services such as drinking water, poor nutrition, slum conditions of housing, and episodes of stress, anxiety, and neglect.

In addition, the inhabitants present adverse conditions of geographic accessibility and topographic characteristics that generate barriers to mobility, accidents, difficulty in accessing different health, supply, education, and public services. In correspondence with the episodes of accidents due to the high slopes of the territory, roads in poor condition, lack of sidewalks, housing design conditions related to spatial distribution and materials, and informal jobs that require physical effort, accidents such as traumas, burns, fractures, contusions, run overs, and sprains can occur. If the impacts related to informal work, structural vulnerability, slum housing, pedestrian and vehicular roads, and artisanal connections to basic services are improved, the probability of suffering from accidents would decrease in the territory.

Similarly, unemployment is high, which leads the population to engage in informal productive activities that are carried out in unsafe conditions and can lead to musculoskeletal accidents or direct exposure to hazardous chemicals, causing respiratory infections and poisoning. These negative effects on health due to physical and emotional alterations arise from being exposed to physical efforts, long working hours, and precarious environmental conditions, which can generate episodes of stress, accidents, and respiratory and gastroenterogenic diseases, affecting their wellbeing and quality of life.

Regarding the perception of public safety in the sector, the community feels partially safe, but this perception decreases when moving to other places necessary to meet the needs of infrastructure for public, commercial, and formal and informal work; so, if access to basic urban infrastructure in the sector is improved, the feeling of well-being of the inhabitants could increase from the perception of safety from theft, threats, extortion, homicides, and sexual abuse. On the other hand, the community stated that by improving housing conditions, domestic violence, personal injuries, and sexual abuse of children under 5 years of age, adolescents, and women would also decrease.

In addition, the inhabitants must travel long distances to work or to meet their basic infrastructure needs, exposing them to episodes of citizen insecurity such as sexual abuse, theft, personal injury, and homicides, which results in the inhabitants being exposed to constant episodes of stress and anxiety. In addition, the permanent lack of economic resources leads the inhabitants of the sector to face constant worries, and with it a high psychosocial burden with continuous states of hopelessness and stress, increasing the risk of suffering from mental illnesses, cardiovascular diseases, nervous system diseases,

and consumption of psychoactive substances. In the territory, young people start the consumption of psychoactive substances from the age of 12 with cigarettes, followed by alcohol and marijuana.

Therefore, in the face of mental illnesses with episodes of depression, insecurity, stress, violence, alcoholism, and drug addiction in the community, it is necessary to improve the comfort and structural vulnerability in housing, citizen security in the territory, during the movements of the inhabitant, the abandonment and abuse of children under 5 years old and the elderly over 60 years old, and the degradation of the landscape, in addition to having safe spaces where physical and meeting activities can be carried out.

To reduce gastroenterogenic diseases reported by the population, such as gastrointestinal infections, food poisoning, and intestinal parasitosis, it is necessary to control and mitigate impacts such as the rental of sanitary facilities and water contamination by excreta due to the use of hoses in conduction and poor food handling. In addition to becoming aware of the constant risk to which they are exposed by these bad practices, it is also necessary to improve housing conditions and provision of formal public services.

Regarding the presence of slums, structural vulnerability, low security of tenure, and hygiene in housing, they increase the possibility of vector and pest diseases, respiratory and cardiovascular diseases, and gastroenterogenic diseases in the population due to constant overcrowding, lack of privacy, poor food handling, and consumption of contaminated water.

In order to reduce episodes related to respiratory diseases such as bronchitis, pneumonia, rhinitis, asthma, and COPD, it is necessary to mitigate the impacts on the territory related to the construction of slums; the degradation of the landscape due to contamination by excreta, sewage, and solid waste; improve the quality of roads in general; and improve comfort in housing. Likewise, with the implementation of sustainable systems such as green roofs, the thermo-acoustic conditions of the house can be improved, prior to a structural evaluation of the house.

Regarding hygiene, diseases caused by vectors and pests, such as rabies, schistosomiasis, and soil-transmitted helminthiasis, are present in the population of Santa Marta, which, by controlling the impacts on the territory of slum construction, contamination by excreta, pollution due to stagnant water, the presence of open conventional and hazardous solid waste, and wastewater discharges, would be considerably reduced in the sector since the population stated during the year that skin infections such as athlete's foot, herpes, pediculosis, and insect bites were conditions that occurred endemically in the inhabitants. Therefore, if the impacts related to diseases were caused by vectors, consumption of contaminated water, poor food handling, and overcrowding in the home, these skin infections would decrease in terms of contagion and number of cases in the community.

Finally, the low quality of air inside homes and in urban areas, the poor disposal of solid waste, the structural and material conditions of the homes, the adverse geographical and topographic conditions, conflicts in land use [63], the lack of infrastructure [64], high migration, the expansion of the territory without planning, the lack of aqueduct and sewage services, and low economic income cause episodes of health disease in the inhabitants of the Santa Marta sector, which means that, if the indicators gradually improve, and the impacts are mitigated, the probability of presenting health-disease episodes in the population would circumstantially decrease.

## 5. Conclusions

The process of quantifying the indicators and evaluating their respective impacts on the territory to relate health-disease episodes in its inhabitants served to demonstrate the direct relationship that exists between neighborhood informality, poverty, and quality of life, as a person who suffers from physical and mental illness cannot be 100% productive and normalizes their habitability situation, unaware that it directly makes them sick, contradicting the collective thought that well-being, and quality of life is found in the city regardless of its location, level of formality, or consolidation of their territories.

Neighborhood informality, combined with the low economic income of families residing in the territory, implies not having the necessary means to meet basic needs in infrastructure, housing, education, and public services, which directly impacts the quality of life from the perspective of public health by constantly presenting episodes of morbidity and mortality in the inhabitants, which increases the perception of vulnerability in the person, normalizing unhealthy habits, unsafe working conditions, and environmental degradation in the territory in air, water, and the land due to its precarious and unsustainable habitability.

The strategy of relating the daily living conditions of the population with variables, indicators, impacts, morbidity, and mortality events helped the inhabitants of the Santa Marta sector to understand that the health-disease episodes they suffer are direct consequences of informality in the occupation of the territory, as the negative impacts identified are directly proportional to a high probability of physical and mental illnesses materializing in the population.

As for the groups of children under 5 years of age and adults over 60 years of age, within the framework of neighborhood informality in the territory, they increase their condition of vulnerability to being more exposed than other age groups to episodes of physical and mental illness given their circumstances. The settlement presents precarious conditions of habitability and sustainability at the urban level. The above, combined with the situation of displacement of the majority of family units, exacerbates the cases of respiratory, gastroenterogen, and mental diseases in the population.

Housing can be considered a determining factor in terms of how the inhabitant relates to their territory in the Santa Marta sector, as, from its illegality, location, construction, and design, bad practices begin that give way to present the identified impacts. With this, the report of the health-disease episodes in the population manifested. It is important that projects framed in the principle of healthy housing in the territory are designed and executed as a strategy to improve the physical and mental health of the inhabitant.

**Author Contributions:** Conceptualization, C.A.T.P., Y.N.S.M., M.G.M., N.V.F., M.G. and N.C.A. Methodology, C.A.T.P., I.F., M.G. and N.C.A. Software, C.A.T.P., N.C.A. and M.G. Validation, Y.N.S.M., M.G.M., I.F. and F.C. Formal analysis, C.A.T.P., Y.N.S.M., M.G.M., N.V.F. and I.F. Investigation, C.A.T.P., Y.N.S.M., M.G.M. and N.C.A. Resources, C.A.T.P., Y.N.S.M., M.G.M., N.V.F., I.F. and M.G. Data curation, C.A.T.P., Y.N.S.M. and N.C.A. Writing—original draft preparation, C.A.T.P., Y.N.S.M. and N.C.A. Writing—review and editing, C.A.T.P., Y.N.S.M., M.G.M., N.V.F., I.F. and M.G. Visualization, C.A.T.P., N.C.A. and F.C. Supervision, M.G.M., N.C.A. and F.C. Project administration, C.A.T.P., Y.N.S.M., M.G.M., N.V.F. and I.F. Funding acquisition, C.A.T.P., Y.N.S.M., M.G.M., N.V.F. and I.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** The resources for the development of research come from the call of the Catholic University of Colombia, grant number: CON0000550. The research units are: Catholic University of Colombia—UCC, Group: Infrastruestructura Y desarrollo sostenible (Colombia); Universidade Federal da Integração Latino-Americana—UNILA, Group: Mobility and energy matrix (Brazil); University of Salerno—UNISA, Group: Technique and urban planning (Italy); and Pontificia Universidad Javeriana PUJ, Group: Ecology and Territory (Colombia).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Acknowledgments:** Thanks to the community leaders of the Santa Marta neighborhood of the town of Ciudad Bolívar in Bogotá, Colombia, for their participation and collaboration in the project, as well as to the staff of the community infrastructure area of the TECHO—Colombia organization for their support during the recognition of the project. Territory, information gathering, and participatory work with the community and this research was funded by MIUR, PRIN 2022, grant number P2022PP8BT.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References


1. Castillo Féliz, H. Evaluación de Ecobarrios en Europa y su Posible Traslación al Contexto Latinoamericano. Ph.D. Thesis, Urbanística y Ordenación del Territorio, Higueras García, Ester, 2013. [CrossRef]
2. Convention on Biological Diversity. ITU Committed to Connecting the World. Obtenido de U4SSC—Collection Methodology for Key Performance Indicators for Smart Sustainable Cities. 2017. Available online: https://www.itu.int/en/publications/ITU-T/pages/publications.aspx?parent=T-TUT-SMARTCITY-2017-9&media=electronic (accessed on 5 September 2023).
3. Fekade, W. Deficits of formal urban land management and informal responses under rapid urban growth, an international perspective. *Habitat Int.* **2000**, *24*, 127–150. [CrossRef]
4. Torres López, E. Desarrollo Urbano Sustentable. Obtenido de Observatorio de la Economía Latinoamericana. 2008. Available online: https://www.eumed.net/cursecon/ecolat/la/08/etl.htm (accessed on 5 September 2023).
5. Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being: The Assessment Series*; Island Press: Washington, DC, USA, 2005.
6. Vera, F.; Sordi, J. Diseño Ecológico: Estrategias Para la Ciudad Vulnerable: Adaptando las Áreas Precarias de América Latina y el Caribe al Cambio Climático. Obtenido de Banco Interamericano de Desarrollo. 2020. Available online: https://publications.iadb.org/es/diseno-ecologico-estrategias-para-la-ciudad-vulnerable-adaptando-las-areas-precarias-de-america (accessed on 5 September 2023).
7. UN-HABITAT. *Cities and Climate Change: Global Report on Human Settlements 2011*; United Nations Human Settlements Programme, Earthscan: London, UK; Washington, DC, USA, 2011; Available online: http://unhabitat.org/books/cities-and-climate-change-global-report-on-human-%20settlements-2011 (accessed on 15 November 2023).
8. European Environment Agency. *Climate Change, Impacts and Vulnerability in Europe 2012*; Publications Office of the European Union: Luxembourg, 2012. Available online: www.eea.europa.eu/publications/climate-impacts-and-vulnerability-2012/climate-change-impacts-and-vulnerability/view (accessed on 15 November 2023).
9. United Nations. 68% of the World Population Projected to Live in Urban Areas by 2050, Says UN. 2018. Available online: www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (accessed on 15 November 2023).
10. Escobar Delgadillo, J.L.; Jiménez Rivera, J.S. Urbanismo y Sustentabilidad: Estado Actual del Desarrollo Urbano de la ZMVM. Revista Digital Universitaria, 10(07). Available online: https://www.revista.unam.mx/vol.10/num7/art40/int40.htm#a (accessed on 10 July 2009).
11. Jim, C.Y. Sustainable urban greening strategies for compact cities in developing and developed economies. *Urban Ecosyst. Vol.* **2012**, *16*, 741–761. [CrossRef]
12. Navarrete Peñuela, M. Desarrollo urbano sustentable: El gran desafío para América Latina y los preparativos para hábitat III. *Luna Azul* **2017**, *45*, 123–149. [CrossRef]
13. Marti'nez Rivera, S.; Tra'paga Delfi'n, Y. *Construyendo Ciudades Sustentables: Experiencias de Peki'n y la Ciudad de Me'xico*; México, D.F., Ed.; Universidad Autónoma de México: Mexico City, México, 2012; Available online: https://dusselpeters.com/CECHIMEX/LibroCiudadesSustentables.pdf (accessed on 5 September 2023).
14. López, M.D. Reconversión urbana desde las políticas estatales. La Plata (Argentina) entre 2007–2015. *Bitácora Urbano Territ.* **2018**, *28*, 63–72. [CrossRef]
15. ONU HABITAT. La Nueva Agenda Urbana. *Obtenido de onu Habitat por un Mejor Futuro Urbano.* 2016. Available online: https://onuhabitat.org.mx/index.php/la-nueva-agenda-urbana-en-espanol (accessed on 5 September 2023).
16. Cifuentes, A.V.; Lufkin, S.; Riera Pérez, M.G.; Rey, E. Sustainability Assessment of an Urban Neighbourhood Revitalization Project in Bogotá, by Transposition of a European Indicator System to the Colombian Context. *WIT Trans. Ecol. Environ.* **2015**, *194*, 79–92.
17. Tapia Zarricueta, R.; Lange Valdés, C.; Larenas Salas, J. Factores de Deterioro del Hábitat Residencial y de Vulnerabilidad Social en la Conformación de Barrios Precarios: Breve Revisión de Algunos Programas de Barrios en Chile y en la Región. In *Cuaderno de trabajo*; Universidad de Chile, Vicerrectoría de Investigación y Desarrollo: Santiago, Chile, 2009; Volume 1, pp. 48–92. Available online: https://repositorio.uchile.cl/bitstream/handle/2250/144796/Factores-de-deterioro-del-habitat-residencial-y-de-vulnerabilidad-social-en-la-conformacion-de-barrios-precarios-breve-revision-de-algunos-programas-de-barrios-en-Chile-y-en-la-region.pdf?sequence (accessed on 5 September 2023).
18. Yunda, J. Aplicabilidad de criterios internacionales de sostenibilidad para evaluar el diseño urbano de barrios periféricos de origen formal e informal en Bogotá. *Rev. Bras. Gestão Urbana* **2019**, *11*. [CrossRef]
19. Camargo Sierra, A.P.; Hurtado Tarazona, A. (agosto de). Urbanización informal en Bogotá: Agentes y lógicas de producción del espacio urbano. *INVI* **2013**, *28*, 77–107. [CrossRef]
20. TECHO Colombia. ¿QUÉ ES TECHO? 2023. Available online: https://colombia.techo.org/sobre-techo/ (accessed on 5 September 2023).
21. United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: www.sustainabledevelopment.un.org (accessed on 15 November 2023).
22. United Nations. World Urbanization Prospects 2018. 2018. Available online: www.population.un.org (accessed on 15 November 2023).
23. UN. The Urban Agenda. 2017. Available online: https://ec.europa.eu/futurium/en/node/1829 (accessed on 15 November 2023).

24. UN. *The Sustainable Development Goals Report 2019*; United Nations: New York, NY, USA, 2019.
25. Huovila, A.; Bosch, P.; Airaksinen, M. Comparative analysis of standardized indicators for Smart sustainable cities: What indicators and standards to use and when? *Cities* **2019**, *89*, 141–153. [CrossRef]
26. Ahvenniemi, H.; Huovila, A.; Pinto-Seppä, I.; Airaksinen, M. What are the differences between sustainable and smart cities? *Cities* **2017**, *60*, 234–245. [CrossRef]
27. Verma, P.; Raghubanshi, A. Urban sustainability indicators: Challenges and opportunities. *Ecol. Indic.* **2018**, *93*, 282–291. [CrossRef]
28. Jaan Lee, Y.; Ming Huang, C. Sustainability index for Taipei. *Environ. Impact Assess. Rev.* **2007**, *27*, 505–521.
29. Zheng, H.; Shen, G.; Song, Y.; Sun, B.; Hong, J. Neighborhood sustainability in urban renewal: An assessment framework. *Environ. Plan. B Urban Anal. City Sci.* **2016**, *44*, 903–924. [CrossRef]
30. Banco Interamericano de Desarrollo. Programa Ciudades Emergentes y Sostenibles (CES). 2023. Available online: https://www.iadb.org/es/desarrollo-urbano-y-vivienda/programa-ciudades-emergentes-y-sostenibles#:~:text=El%20Programa%20Ciudades%20Emergentes%20y,de%20planes%20de%20sostenibilidad%20urbana (accessed on 5 September 2023).
31. Moreno García, R.; Inostroza Seguel, L. Sostenibilidad Urbana: Análisis a Escala Barrial en la Ciudad de Temuco, Chile. *Arquit. Rev.* **2019**, *15*, 103–116. [CrossRef]
32. Observatorio de Medio Ambiente Urbano. Agenda Urbana Málaga. Indicadores de Sostenibilidad 2016. Obtenido de OMAU Observatorio de Medio Ambiente Urbano—Ayuntamiento de Málaga. 2016. Available online: https://www.omau-malaga.com/22/indicadores-agenda (accessed on 5 September 2023).
33. Bogotá Cómo Vamos. Informe de Calidad de Vida 2021. Obtenido de Bogotá Cómo Vamos. 2022. Available online: https://bogotacomovamos.org/categoria/informes-de-calidad-de-vida/#:~:text=El%20Informe%20de%20Calidad%20de,la%20Bogot%C3%A1%20del%20siglo%20XXI%E2%80%9D (accessed on 5 September 2023).
34. Alcaldía Local de Ciudad Bolivar. Diagnóstico Local Ciudad Bolívar 2020. Obtenido de Alcaldía Local de Ciudad Bolivar. 2020. Available online: http://ciudadbolivar.gov.co/transparencia/planeacion/participacion-ciudadana/diagnostico-local-ciudad-bolivar-2020 (accessed on 5 September 2023).
35. Cheshmehzangi, A.; Dawodu, A.; Song, W.; Shi, Y.; Wang, Y. An Introduction to Neighborhood Sustainability Assessment Tool (NSAT) Study for China from Comprehensive Analysis of Eight Asian Tools. *Sustainability* **2020**, *12*, 2462. [CrossRef]
36. Grazieschi, G.; Asdrubali, F.; Guattari, C. Neighbourhood sustainability: State of the art, critical review and space-temporal analysis. *Sustain. Cities Soc.* **2020**, *63*, 102477. [CrossRef]
37. Hernández Sampieri, R.; Fernández Collado, C.; Baptista Lucio, P. *Metodología de la Investigación*, 6th ed.; México, D.F., Ed.; Mc Graw Hill: Mexico City, México, 2014; Available online: https://www.uca.ac.cr/wp-content/uploads/2017/10/Investigacion.pdf (accessed on 5 September 2023).
38. Torres Parra, C.A.; Saldeño Madero, Y.N.; Castiblanco Prieto, J.J.; García Ubaque, C.A. *Propuesta de Diagnóstico de Habitabilidad en Asentamientos Humanos a Nivel Urbano*; Universidad Católica de Colombia: Bogotá, Colombia, 2020.
39. Freeman, A.M. *The Measurement of Environmental and Resource Values. Theory and Methods*; Resources for the Future: Washington, DC, USA, 1993.
40. Hördur, H.; Salim, B.; Harald, S. Causal Loop Diagrams–Promoting deep learning of complex systems in engineering education. In Proceedings of the 4th Pedagogical Inspiration Conference, Lund, Sweden, 1 June 2006; Available online: https://www.lth.se/fileadmin/lth/genombrottet/konferens2006/Haraldsson_etal_bidrag.pdf (accessed on 5 September 2023).
41. Baugh Littlejohns, L.; Baum, F.; Lawless, A.; Freeman, T. The value of a causal loop diagram in exploring the complex interplay of factors that influence health promotion in a multisectoral health system in Australia. *Health Res. Policy Syst.* **2018**, *16*, 126. [CrossRef]
42. Sahin, O.; Salim, H.; Suprun, E.; Richards, R.; MacAskill, S.; Heilgeist, S.; Rutherford, S.; Stewart, R.A.; Beal, C.D. Developing a Preliminary Causal Loop Diagram for Understanding the Wicked Complexity of the COVID-19 Pandemic. *Systems* **2020**, *8*, 20. [CrossRef]
43. Espinoza, G. Fundamentos de evaluación de impacto ambiental. Banco Interamericano de Desarrollo. In *BID y Centro de Estudios para el Desarrollo*; CED: Santiago, Chile, 2002.
44. Figueroa, A.; Contreras, R.; Sánchez, J. *Evaluación de Impacto Ambiental. Un instrumento para el Desarrollo*; Centro de Estudios Ambientales para el Desarrollo Regional, Corporación Autónoma de occidente: Cali, Columbia, 1998.
45. FINDETER. *El Impacto Ambiental en Los Proyectos de Desarrollo*; FINDETER: Santafé de Bogotá, Columbia, 1992.
46. Ramírez, M.C.; Bengo, I.; Mereu, R.; Bejarano, R.A.X.; Silva, J.C. Participative Methodology for Local Development: The Contribution of Engineers Without Borders from Italy and Colombia: Towards the Improvement of Water Quality in Vulnerable Communities. *Syst. Pract. Action Res.* **2011**, *24*, 45–66. [CrossRef]
47. Macchiaroli, M.; Dolores, L.; Nicodemo, L.; De Mare, G. Energy Efficiency in the Management of the Integrated Water Service. A Case Study on the White Certificates Incentive System. In *Computational Science and Its Applications—ICCSA 2021*; Lecture Notes in Computer, Science, Gervasi, O., Eds.; Springer: Cham, Switzerland, 2021; Volume 12956. [CrossRef]
48. Plazas Certuche, J.A.; de JLema Tapias, Á.; León Peláez, J.D. Una propuesta estadística para la evaluación del impacto ambiental de proyectos de desarrollo. *Rev. Fac. Nac. De Agron. Medellín* **2009**, *62*, 4937–4955.
49. Sanz, J. Concepto de Impacto Ambiental y su Evaluación. In *Evaluación y Corrección de Impactos Ambientales*; Ayala, F., Ed.; Instituto Tecnológico Geominero de España: Madrid, Spain, 1991; pp. 27–38.

50. Ospina, J.E.; Lema, Á.D.J. Indicadores cuantitativos de los impactos generados en proyectos de desarrollo lineales. *Gestión Ambiente* **2004**, *7*, 91–112.
51. León, J.D. *Evaluación de Impacto Ambiental de Proyectos de Desarrollo*; Centro de Publicaciones Universidad Nacional de Colombia: Medellín, Colombia, 2004; 366p.
52. Peláez, J.D.L.; Arango, G.J.L. Propuesta metodológica para la evaluación de impacto ambiental a partir de diferentes métodos específicos. *Rev. Fac. Nac. Agron.* **1999**, *52*, 565–598.
53. Gómez, O.D. Evaluación de impacto ambiental (EIA). *Ciudad. Territ.* **1988**, *75*, 5–32.
54. Gómez, O.D. *Evaluación del Impacto Ambiental. Un Instrumento Preventivo Para la Gestión Ambiental*; Mundi-Prensa y Editorial Agrícola Española: Madrid, Spain, 1999; 701p.
55. Conesa, F.V. *Guía Metodológica Para la Evaluación del Impacto Ambiental*; Mundi-Prensa: Madrid, Spain, 2003; 416p.
56. Canter, L. *Manual de Evaluación de Impacto Ambiental*; Técnicas Para la Elaboración de los Estudios de Impacto; Segunda edición; McGraw Hill: Madrid, Spain, 1998; 841p.
57. Arboleda, J. Una propuesta para la identificación y evaluación de impactos ambientales. *Crónica For. Y Medio Ambiente* **1994**, *9*, 71–81.
58. Arboleda, J. *Manual Para la Evaluación de Impacto Ambiental de Proyectos*; Obras o Actividades: Medellin, Colombia, 2008.
59. García Ubaque, J.C.; García Ubaque, C.A.; Torres Parra, C.A. Habitabilidad de la Vivienda: Una Perspectiva de Salud; Universidad Nacional de Colombia: Colombia. 2017. Available online: https://medicina.bogota.unal.edu.co/dependencias/unidades/publicaciones/item/1194-habitabilidad-de-la-vivienda (accessed on 5 September 2023).
60. Lichfield, N. *Community Impact Evaluation: Principles and Practice*; Taylor & Francis e-Library: London, UK, 2005.
61. Secretaría Distrital de Salud. Análisis de Condiciones, Calidad de Vida, Salud y Enfermedad Localidad Ciudad Bolivar. 2017. Available online: https://repositorio.saludcapital.gov.co/handle/20.500.14206/4537 (accessed on 5 September 2023).
62. Catalina, R.; Jaime, P.-T.; Camilo, T.; Juan, S.; Luis, C.; Miguel, G. A Systemic Framework to Develop Sustainable Engineering Solutions in Rural Communities in Colombia. *Syst. Pract. Action Res.* **2012**, *25*, 95–116.
63. Gerundo, R.; Marra, A.; Giacomaniello, O. Una metodologia per analizzare il ruolo della vulnerabilità ambientale nei processi di periferizzazione su scala urbana e metropolitana. In *Innovazione Nella Pianificazione Urbana e Territoriale*; INPUT 2021; Lecture Notes in Civil Engineering; La Rosa, D., Privitera, R., Eds.; Springer: Cham, Switzerland, 2021; Volume 146. [CrossRef]
64. Grimaldi, M.; Sebillo, M.; Vitiello, G.; Pellecchia, V. Planning and Managing the Integrated Water System: A Spatial Decision Support System to Analyze the Infrastructure Performances. *Sustainability* **2020**, *12*, 6432. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

Article

# Mining Social Media Data to Capture Urban Park Visitors' Perception of Cultural Ecosystem Services and Landscape Factors

**Yaxin Chen [1], Chuanchun Hong [1], Yifan Yang [2], Jiaxin Li [1], Yu Wang [1], Tianyu Zheng [1], Yinke Zhang [3,*] and Feng Shao [1,*]**

[1] School of Landscape Architecture, Zhejiang Agriculture and Forestry University, Hangzhou 311300, China; chenyaxin@stu.zafu.edu.cn (Y.C.); hongchuanchun@stu.zafu.edu.cn (C.H.); lijiaxin@stu.zafu.edu.cn (J.L.); wangyu8@stu.zafu.edu.cn (Y.W.); zhengtianyu@stu.zafu.edu.cn (T.Z.)
[2] Nature Conservation (National Park) Division, East China Academy of Inventory and Planning of National Forestry and Grassland Administration, Hangzhou 310019, China; ivana1804@stu.zafu.edu.cn
[3] Hangzhou Botanical Garden, Hangzhou 310012, China
* Correspondence: zykedu@outlook.com (Y.Z.); shaofeng@zafu.edu.cn (F.S.); Tel.: +86-1585-815-8022 (Y.Z.); +86-1345-682-9121 (F.S.)

**Abstract:** Urban parks not only enhance urban ecology but also play a crucial role in providing cultural ecosystem services (CESs) for the well-being of urban residents. Both artificial and natural landscape factors within parks contribute significantly to the supply of cultural ecosystem services. To explore public perceptions of landscape factors and CESs, this study focused on 25 urban parks in Hangzhou. Social media data uploaded by park visitors from 2018 to 2023 were collected to establish a corresponding CES indicator framework. Combining computer vision with text mining, we assessed the preferences and correlations between visitor-perceived CESs and park landscape factors. The results indicated that the majority of park visitors perceive CESs (80.00%) with overall satisfaction higher than importance. Among them, aesthetic experiences and recreation showed both high satisfaction and importance. In shared social media photos, arbors (19.01%), herbaceous flowers (8.99%), and groves (8.22%) were frequently presented as landscape factors. The study revealed close correlations between user gender, landscape factors, and perceived CES categories, with females contributing more to the perception of both. There were internal correlations within CES categories, with spiritual services, aesthetic experiences, and recreation showing the most significant associations. Different landscape factors impacted CES categories to varying degrees, and biological landscapes formed by plant and animal factors were considered to provide more CESs. These findings are significant for enhancing the quality of ecological services and biodiversity in parks.

**Keywords:** urban parks; cultural ecosystem services; landscape factors; public perception; social media data; machine learning

**Citation:** Chen, Y.; Hong, C.; Yang, Y.; Li, J.; Wang, Y.; Zheng, T.; Zhang, Y.; Shao, F. Mining Social Media Data to Capture Urban Park Visitors' Perception of Cultural Ecosystem Services and Landscape Factors. *Forests* **2024**, *15*, 213. https://doi.org/10.3390/f15010213

Academic Editor: Isabella De Meo

Received: 6 December 2023
Revised: 12 January 2024
Accepted: 15 January 2024
Published: 21 January 2024

**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The development of urbanization constrains the natural environment in urban areas. Urban parks have become increasingly important as spaces for urban residents to connect with nature and engage in social interactions [1]. Throughout the lengthy process of urban development, urban parks have accumulated rich and irreplaceable natural and cultural heritage, holding high potential value in aesthetics, ecology, and archaeology [2]. The accumulation of these resources makes urban parks the primary source of urban ecosystem services [3,4]. The Millennium Ecosystem Assessment defined ecosystem services as the benefits people obtained from ecosystems, categorizing them into four main types: supporting, regulating, provisioning, and cultural [5]. As a crucial component of ecosystem services, cultural ecosystem services (CESs) refer to the non-material benefits people derive

from ecosystems through spiritual fulfillment, cognitive development, reflection, and aesthetic experiences [5]. They holds enormous potential for improving biodiversity, human mental and physical well-being, and more [6]. Urban park CESs directly reflect the interaction between humans and ecosystems [7], constituting the subjective perception process of individuals toward objective ecological systems. Effectively understanding residents' perceptions regarding CESs provided by green and blue areas within urban parks is important. It contributes to better providing residents with the specific CESs they need and strengthening residents' commitment to environmental conservation [6,8]. However, due to the subjective and intangible nature of CESs, traditional methods face challenges in objectively assessing and quantitatively analyzing them [9,10]. Therefore, identifying and evaluating CESs pose specific challenges [10,11].

Currently, CES evaluation relies on monetization and non-monetization methods [12]. Recently, more researchers have used non-monetization methods to qualitatively and quantitatively analyze CES preferences and perceptions. Methods include participatory mapping with GIS [13] and the SolVES model [14]. With the efficient economic data mining of big data, CES research methods are becoming more informative [2]. Photos [15] and comments [16] on various platforms, along with historical materials like poems and ancient texts [2], can be used to identify CESs. These data serve as information carriers, recording stakeholders' perspectives on cultural services and landscape features while describing changes over time and space [2,17]. Although photo data are widely used, they cannot capture all CES categories alone. Intangible benefits like inspirational values and spiritual experiences are challenging to identify through visual content alone [18,19]. Natural Language Processing (NLP) analysis can provide more information by explicitly expressing users' motivations, viewpoints, experiences, perceptions, or symbolic meanings [17,20]. Additionally, the NLP method is also commonly used to mine emotions in text and is widely applied on platforms such as Twitter [15] and Instagram [21]. Analyzing visitors' emotions helps understand the demands for CESs in urban ecosystems.

Due to the non-random distribution of CESs in urban ecosystems, they exhibit highly localized patterns, leading to hotspots and cold spots of CES flow [22]. To facilitate the rational allocation of environmental resources within ecosystems, scholars have actively explored the factors that may affect CESs. These features include different land cover types, the size of green spaces, respondents' occupations and ages, and the openness of the landscape [6,23–25]. Notably, various natural and artificial landscapes, such as water bodies, birds, sculptures, and recreational elements, can provide a broad range of CESs, sometimes even more comprehensive than the ecosystem [26,27]. Therefore, by examining visitors' detailed and specific landscape factors and CES preferences, we can better understand the interaction between people and nature in urban parks [26]. Previous studies on CESs and landscape factors in urban parks have primarily focused on a small scale, utilizing offline methods such as face-to-face interviews or participatory mapping [28,29]. These studies often employ manual visual interpretation methods [26,30], which are time-consuming, suitable for small amounts of data, and subject to the inherent subjective biases of researchers [9]. To address this issue, the combination of computer vision and social media photos has begun to be used in extracting perceptual information. However, there is currently relatively little research on the correlation between landscape factors and CESs using this combination [9].

In recent years, scholars have studied how urban park characteristics impact consumer electronics product provision. These studies focus on specific cultural service categories [22,31,32], like aesthetics, or particular urban park types [24,33]. Despite scholars identifying associative rules among CES categories [34,35], there is a lack of comprehensive analysis of the diversity of CES categories and their internal correlations. This may be influenced by data types. Most studies on the correlation between CESs and landscape factors rely on a single data type [9]. Some studies integrate text, tags, and photos [20] but need an analysis process suitable for large-scale data. With social media growth and residents' interest in natural ecology, an efficient process for analyzing large-scale CES

perception datasets across time and space is necessary. There were supply and demand differences in CESs in urban parks, but most studies only examined CES supply perception. For example, Riechers et al. [36] studied the impact of age and residence on the perceived importance of cultural ecosystem services. Research on user satisfaction and expectations (supply) for various CES sub-items is still limited [37]. Considering the aforementioned research gaps, this study focused on urban parks in Hangzhou, attempting a novel research approach—integrating computer vision and text mining methods. We combined the advantages of text and image data to extract CES categories and visitors' emotional attitudes from Weibo comments and landscape factors from Weibo photos to obtain a more comprehensive understanding of CES categories and landscape factors. The research aimed to address the following issues: (1) understanding the CES categories of urban parks as well as the satisfaction and expectations of park visitors; (2) effectively extracting the landscape factor preferences of park visitors; and (3) exploring the impact of internal correlations and landscape heterogeneity within CESs. This study provides a new perspective for evaluating the framework of cultural ecosystems in urban parks, contributing to the coordinated development of public perception and planning management. It offers a scientific basis to rationally allocate environmental resources, optimize the efficiency of cultural services in urban parks, and enhance the well-being of urban residents.

## 2. Materials and Methods

### *2.1. Study Area*

Hangzhou (E118°20′–120°37′, N29°11′–30°34′) is located in the Yangtze River Delta, serving as the economic, cultural, and educational center of Zhejiang Province. It is a significant scenic tourist city with rich ecological and cultural resources. Throughout history, the interaction and coexistence of the three major landscape factors (mountains, lakes, and cities) have shaped the long-term relationship between human habitation and the natural environment. The construction of urban parks in Hangzhou has left behind a wealth of perceptual information about the harmonious coexistence of humans and nature. Furthermore, Hangzhou has been a pioneer in constructing urban parks in China. Using Hangzhou as an example, the results of this study have implications that can be valuable for other cities in China and even globally [38].

The study area in this paper was based on the core areas delineated by the 'Hangzhou Green Space System Planning (Revised Edition) (2021–2035)', which include Xihu District, Shangcheng District, Binjiang District, and Gongshu District. These areas are significant carriers of Southern Song culture, Wuyue culture, and Qiantang River culture, with numerous historical sites. These cultural accumulations make these regions rich in tourism resources, with prominent cultural heritage, providing abundant information for CES analysis. In addition, the vegetation structure in the core area is complex, and the vegetation types are diverse. This makes these areas rich in plant resources and high in vegetation coverage, with the West Lake area having the highest forest coverage, reaching 42.60%. Simultaneously, many popular urban parks have been formed during the long process of the transformation and protection of the West Lake Scenic Area in the core area. Therefore, considering three main criteria, we selected representative urban parks within these four districts as our research objects. First, the parks should have a large scale of visitation, with sufficient comment data on social media [19] (filtered for urban parks with posts exceeding 50 pages on Weibo webpages). Second, the parks being studied should have outstanding performance in historical and cultural aspects, plant landscapes, urban characteristics, etc. Third, they should adhere to industry standards. According to industry standards, parks with an area exceeding ten $hm^2$ that can provide various activities are considered comprehensive. Parks with independent land use and an area greater than one $hm^2$ are classified as community parks. Parks with specific themes are categorized as specialized parks. In addition to botanical gardens, zoos, heritage parks, and historic gardens, specialized parks include other specific types such as children's, waterfront, urban forest, and urban wetland parks. Previous academic research has shown that online discussions and

visits to community parks are relatively low [39]; hence, they did not appear in this study. Ultimately, based on the screening of the three criteria, we selected twenty-five distinctive urban parks (Figure 1), categorized into two main groups and eleven subcategories (refer to Appendix A Table A1 for specific classification details).

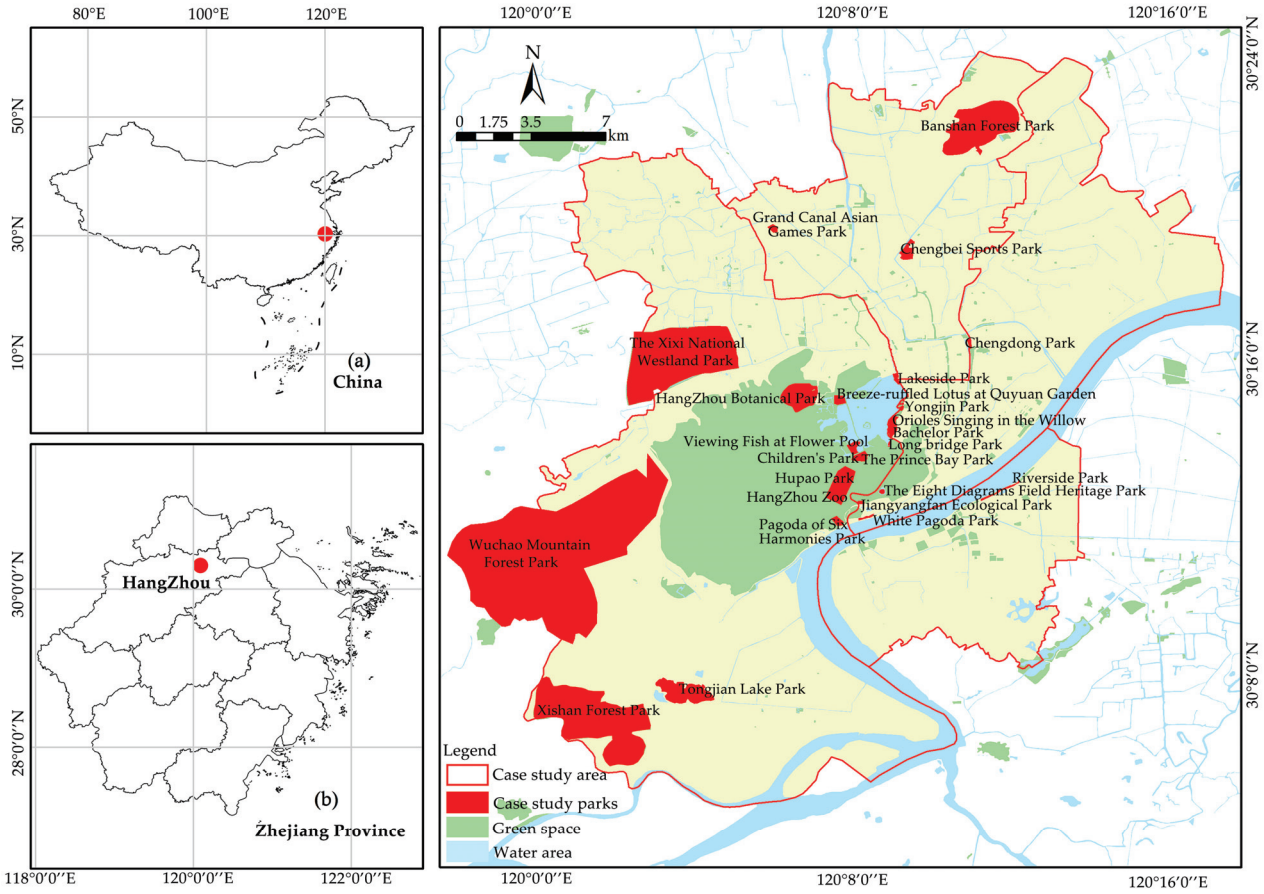



**Figure 1.** Overview map of the research site.

### *2.2. Research Design*

This study utilized social media data that combine text and images to correlate CESs with park landscape factors, conducting a perceptual assessment of CESs in urban parks. The research process consisted of the following four steps (Figure 2): (1) Extracting CESs from text using Natural Language Processing (NLP): Jieba 0.42.1 was applied to preprocessed text data to obtain word frequency statistics, and a professional team was employed for coding and constructing a CES perception information lexicon. (2) Using machine learning to identify landscape factors in photos: the YOLO v5 model was trained to extract landscape factors from preprocessed image data and construct a landscape factor perception system. (3) Correlation analysis: SPSS software and IBM SPSS Modeler software were used to conduct an internal correlation analysis of CES categories and a corresponding analysis with landscape factors. (4) IPA evaluation of CESs: using the Baidu AI intelligent platform to conduct a sentiment analysis on text data, visitor satisfaction with CESs was calculated and combined with CES coding statistics (importance) to construct an IPA evaluation structure.

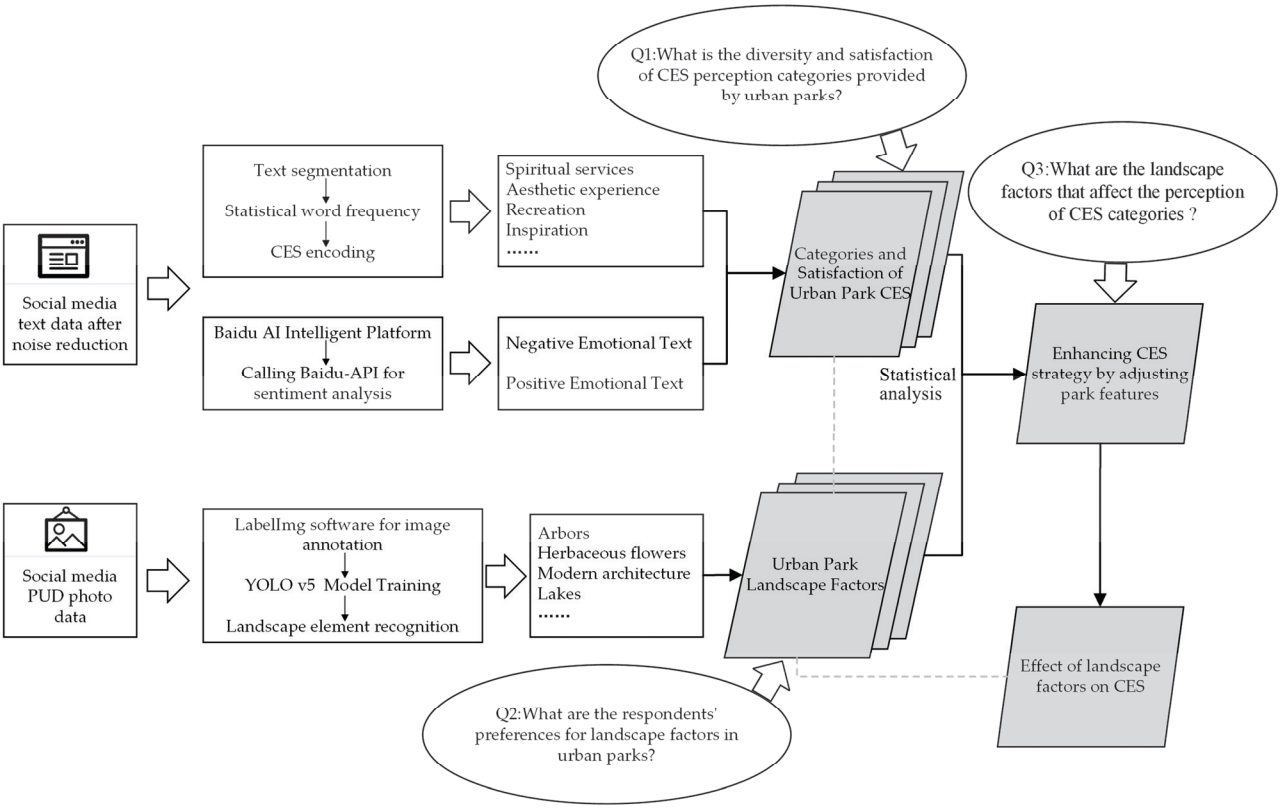



**Figure 2.** Practice-oriented workflow for the case study.

### *2.3. Acquisition of Social Media Data*

Social media data, shared by users in digital formats (text, images, and videos), constitute a valuable information source for the collective perception of diverse landscapes [26], serving as a crucial basis for analyzing the perceived cultural services by park visitors. Sina Weibo is the largest social media platform in China, with over 500 million users as of May 2020, accounting for 42.30% of all internet users, providing rich information and data. Therefore, this study used the Python programming language to obtain data from the Sina Weibo application programming interface (API). The data covered a time range from 1 January 2018 to 4 April 2023, with 62,450 metadata items. Raw, crawled social media data often contain a lot of noise and need to be cleaned. We used the Python programming language and Excel statistical software to remove news, advertisements, and data without actual content. At the same time, we also deleted metadata that did not publish photos. Using Panda's library in the program, we traversed the data. Then, we identified and randomly selected User–Day (PUD) photos, i.e., the unique combination of users and dates, to avoid excessive representation of some active users [9]. Finally, we obtained 17,266 analyzable data points. According to the latest Weibo User Development Report released on the official Weibo website, the user demographic on Weibo continued to show a trend toward a younger audience in 2020, with users aged 19–51 accounting for 96.00%. Therefore, this study's Weibo image and comment data primarily originated from middle-aged and young demographics.

### *2.4. Processing of Social Media Data*

#### 2.4.1. Framework for Urban Park CESs and Landscape Factor Indicators

We referred to authoritative CES indicator classification schemes such as the Millennium Ecosystem Assessment [5], the International Classification of Ecosystem Services [40], and Ecosystems and Biodiversity Economics [41]. Based on the characteristics of Weibo data and on-site investigations, we finally selected the following nine indicators as the CES categories for this study (Table 1): spiritual services, aesthetic experiences, recreation,

inspiration, existential values, cultural heritage, science education, social interaction, and natural appreciation. Building upon the research of previous scholars on cultural ecosystem services and some landscape factors [42–45], we identified 39 relevant landscape factors. A well-established YOLO model was employed to recognize these 39 landscape factors in photos from 25 parks. Factors such as 'food', 'crowd', 'person', 'sunset', and 'night scene' unrelated to actual park construction were excluded to mitigate the impact of collinear data and outliers. In addition, we also removed the factor of perception frequency below 50 times (considered lower compared to 17,266 photos). Similar factors were merged, for example, combining 'Tree flowers' and 'Color leaf trees' into 'Arbors' and categorizing 'Massifs' as 'Groves'. This process resulted in a final list of 21 landscape factors related to cultural ecosystem services, including lakes, ponds, natural revetments, arbors, herbaceous flowers, and others. Following the classification of landscape design factors by American landscape designer Norman K. Booth [46], these factors were categorized into four categories of urban landscapes: hydrological landscape, biological landscape, architecture landscape, and facility landscape.

**Table 1.** CES perceived information dictionary.

| CES Categories | Indicator Connotation | Code | Partially Matched Keywords |
|---|---|---|---|
| Spiritual services | Forgetting worries and feeling respect for nature. | C1 | Full of vitality, enrich, satisfaction, spirit, leisure, feel grateful |
| Aesthetic experiences | Experience the charming scenery, attractions, sounds or smells here. | C2 | Floral fragrance, beautiful scenery, super good-looking, spring scenery, beautiful |
| Recreation | Conduct various leisure and recreational activities in urban parks. | C3 | Recreation, picnic, take a walk, take a picture, fly a kite, climb mountain, boating |
| Inspiration | The artistic inspiration inspired by the park landscape. | C4 | Inspiration, creation, design, interests, inquisitive, thought, crafty |
| Existential values | A place that can generate a sense of connection and belonging, leading to nostalgia. | C5 | Sense of belonging, landmark building, landmark, cherish the memory of, famous, symbolize |
| Cultural heritage | The cultural and historical value contained in urban parks. | C6 | History, culture, artistic atmosphere, cultural atmosphere, cultural heritage |
| Science education | Obtaining knowledge, science popularization, and educational opportunities through urban parks. | C7 | Education, exhibition, commemoration, study, significance, knowledge, museum |
| Social interaction | Promoting social interaction between people. | C8 | Strolling baby, with family, exchange, share, gather, connection, communicate |
| Natural appreciation | Experience the pleasure of watching or interacting with animals and plants. | C9 | Plant, animal, ornamental flowers, ornamental plant leaves, insect, feed fish, watch fish |

#### 2.4.2. Establishment of CES Perception Lexicon

The preprocessed text data underwent secondary processing, removing emoticons and spaces from the text. We used the Jieba 0.42.1 in Python to segment the comment data and annotate parts of the speech. To increase the accuracy of segmentation in the professional domain, based on the relevant literature [17,47,48], we loaded the Harbin Institute of Technology stop word dictionary [49] and a custom dictionary (829 terms) and then replaced synonyms. Due to the extensive database, we conducted word frequency statistics on the segmentation and retained high-frequency words with a frequency greater than six (to avoid ambiguity, the frequency of single-character words was not counted). We referred to the grouping of text word frequency in the literature [9,22,35]. Then, we used the Delphi expert evaluation method [17], established a coding team of 10 professionals,

and coded high-frequency words with a frequency greater than 5 in 25 parks. For disputed parts, we recoded them multiple times until we reached a consensus. Each text could be coded into multiple landscape categories. We used Python programs to convert each text-encoded form and check the CES information of the text that had not yet been encoded. Finally, the CES perception information lexicon was constructed (Table 1).

#### 2.4.3. Landscape Factor Extraction Based on Image Annotation

YOLO v5 is currently one of the mainstream target detection models in the YOLO (You Only Look Once) series [50]. Compared to SD and Mobile Net, the YOLO algorithm is a lightweight neural network with few parameters, a fast operation speed, and relatively high accuracy. The YOLO model consists of four parts: the input end, the backbone (primary network), the neck network, and prediction (output end) [51] (Figure 3). In addition to vehicle and pest recognition applications, the YOLO model can effectively identify landscapes. For example, Wang et al. [52] effectively identified images of Mount Lu based on an improved YOLO v4. For this study, we trained the YOLO v5 model using the Anaconda-Py 3.10 environment for Weibo photo data. The target recognition process was as follows: (1) The preparation of a photo training set for landscape factor recognition. We randomly selected 4300 photos from the preprocessed photo data and manually annotated them using Labelimg 1.8.5 annotation software. The landscape labels included 39 categories, such as herbaceous flowers, arbors, lawns, lakes, birds, and identification facilities. These preprocessed photos were randomly divided into training and validation sets in a ratio of 3:1. (2) The dataset was trained for 200 iterations, and a balance was reached at 120 iterations. The accuracy of the validation set converged without significant improvement, indicating that the model training was completed.

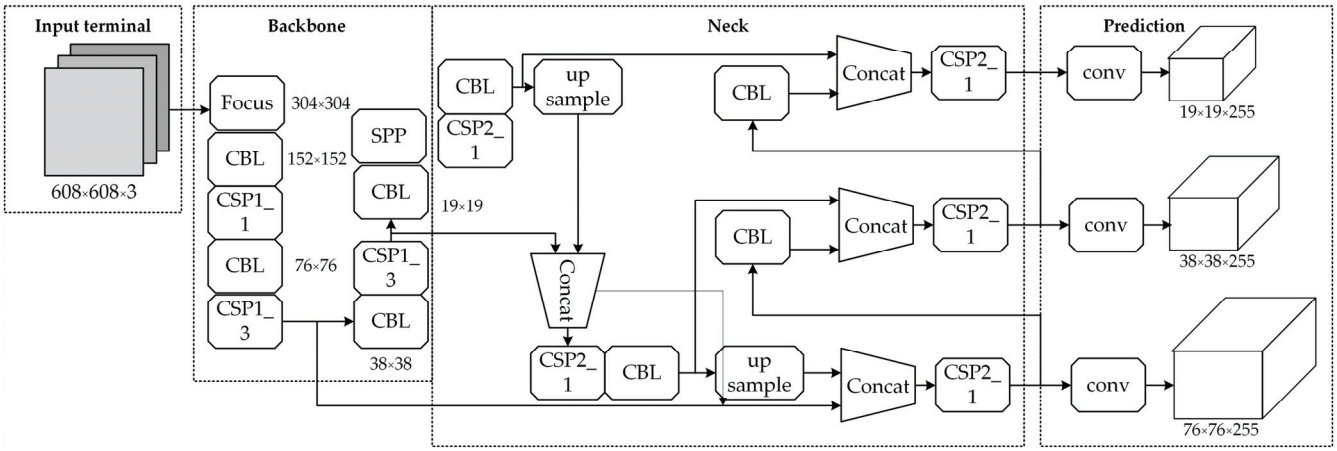



**Figure 3.** YOLO v5 model structure diagram.

We used a confusion matrix to compare the image annotation results performed by the YOLO v5 model with the author's obtained image annotation results to evaluate the accuracy of the image annotation results. Based on the confusion matrix, we calculated True Positives (TP), True Negatives (TN), False Positives (FP), and False Negatives (FN) for the 21 selected landscape factors. TP represent positive results correctly predicted by the model, TN denote negative results correctly predicted by the model, FP represent positive results incorrectly predicted by the model, and FN represent negative results incorrectly predicted by the model. We calculated the precision (Equation (1)), recall (Equation (2)), mAP@0.5, and mAP@[0.5 = 0.95].

$$Precision = \frac{TP}{TP + FP} \quad (1)$$

$$Recall = \frac{TP}{TP + FN} \quad (2)$$

### 2.5. Data Statistical Analysis

This study used IBM SPSS Modeler 18.0 software for an Apriori algorithm analysis of internal association rules for CES categories. A Multiple Correspondence Analysis (MCA) could reveal the relationship between multiple categorical variables through the score distances on intuitive graphs. Then, based on the results of the Weibo text data analysis (CES coding statistics, sentiment analysis), we used an IPA to analyze the differences between users' perceptions of the importance of CESs and experience satisfaction. This kind of analysis helps propose targeted strategies for improving the quality of CESs in Hangzhou city parks [53]. Perceived importance was measured by the frequency of occurrences of cultural ecosystem service categories, and experience satisfaction was measured by the proportion of positive text in the text data. The Baidu AI open platform's emotion analysis module completed the emotional judgment of visitors' uploaded texts. All statistical analyses and data plotting were performed in Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA, USA), Python 3.11.4 (Python Software Foundation, Wilmington, NC, USA), SPSS 26 (International Business Machines Corporation, Armonk, NY, USA), and IBM SPSS Modeler 18.0 software (International Business Machines Corporation, Armonk, NY, USA).

## 3. Results

### 3.1. CESs in Social Media Texts

#### 3.1.1. The Similarities and Differences in the Perceptions of Urban Park CESs

The gender ratio of the visitors in the 25 urban parks was 2.26:1, with 57.64% of the visitors being from outside the province and 42.34% from within the province. Out of 17,266 text data points, we counted 7371 words with a frequency greater than six, which were counted and encoded as 985 words as CES perception information. Approximately 14,737 texts reflected visitors' perceptions of CESs, accounting for 85.35%. The overall perception frequency of CESs was above 80.00%, with 13 parks having a perception frequency exceeding 90.00%, accounting for 52.00%. All CES categories were perceived in the various parks, but there were differences among different parks (as shown in Figure 4). The perception frequencies of spiritual services, aesthetic experiences, recreation, and natural appreciation were significantly prominent. Aesthetic experience and recreation had relatively even distribution ratios in the various parks, around 19.00% (Figure 5).

Figure 4 presents the CES frequencies in different types of parks. The comprehensive parks had a total of 7585 text records and 19,412 CES code records documenting visitors' perceptions of CESs. Among them, Prince Bay Park and White Pagoda Park had the highest frequency of perception keywords, accounting for 25.85% and 24.52%, respectively. In the 7152 perception records of specialized parks, there were 21,077 CES code entries, with zoos ($n$ = 4770, 22.63%) and botanical gardens ($n$ = 6431, 30.51%) showing a significant advantage in the quantity of perceived CES code entries. According to Figure 5, the aesthetic experience function of Tongjian Lake Park and the leisure and recreation function of White Pagoda Park had the highest proportions among all CESs in their respective parks, accounting for 38.16% and 32.04%, respectively. Spiritual services and natural appreciation had average ratios of 12.99% and 14.69%, respectively, ranking only behind aesthetic experience and recreation. The differences in historical and cultural perceptions among the different parks were substantial, with the highest being in the Eight Diagrams Field Heritage Park at 23.96% and the lowest in Hangzhou Zoo at 2.54%. Social interaction was prominent in Children's Park and Hangzhou Zoo, accounting for 17.00% and 12.29%, respectively. These data indicated that the public prefers social activities in these two parks. Among all the parks, only a few visitors perceived inspiration, existential values, or science education (all below 6.20%), with inspiration having the lowest perception frequency.

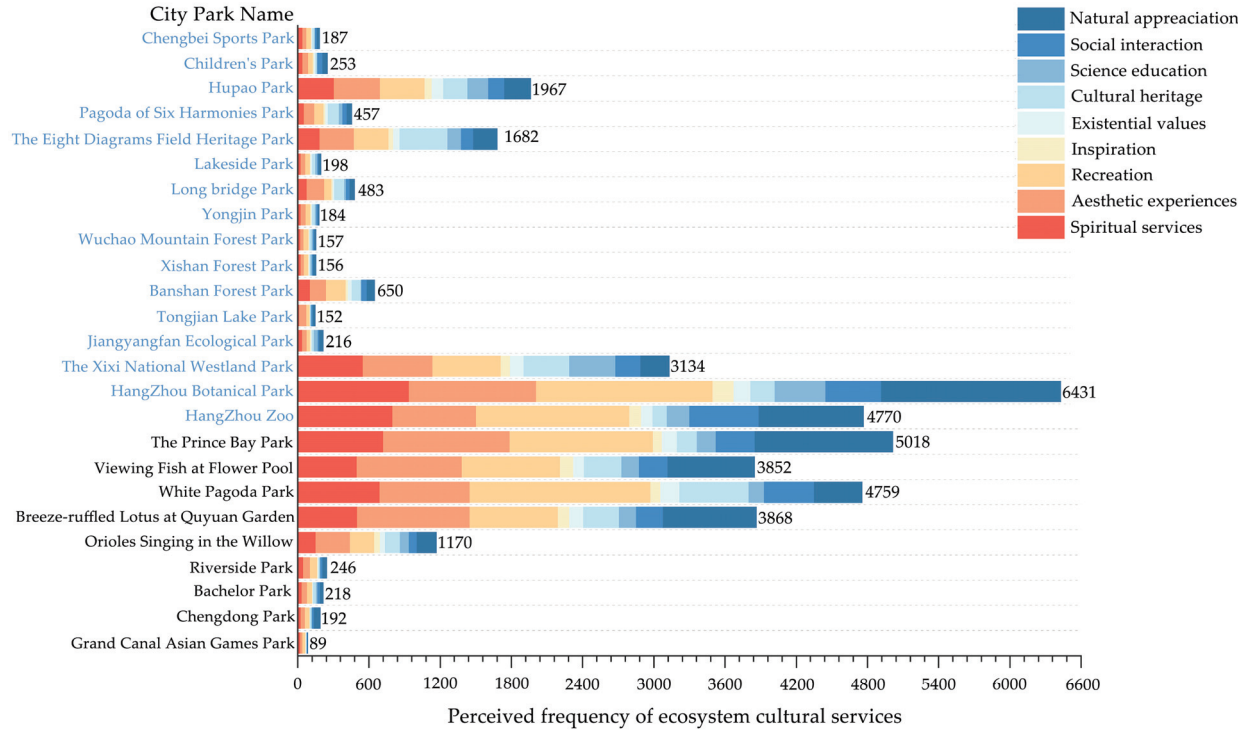



**Figure 4.** Overall perception bar chart of urban park CESs (the park names in blue font are dedicated parks; the park names in black font are comprehensive parks).

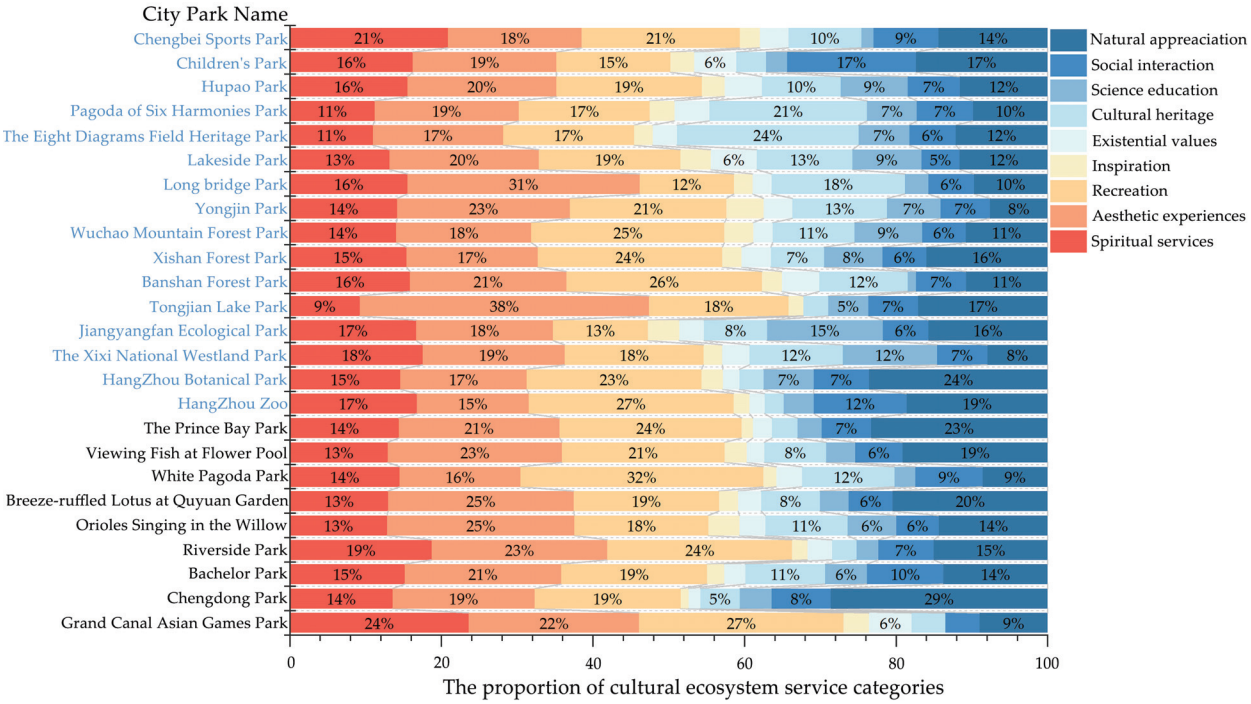



**Figure 5.** Distribution of CES perception types in urban parks (the park names in blue font are dedicated parks; the park names in black font are comprehensive parks).

### 3.1.2. Importance–Performance Analysis of Visitors at Urban Park CESs

According to the emotional value statistics processed by the Baidu AI Open Platform's sentiment analysis module, visitors' positive Weibo texts had the highest proportion (92.07%, $n$ = 15,897), followed by negative texts (6.60%, $n$ = 1139), and neutral texts (1.32%, $n$ = 230). Table 2 shows the results of the visitors' ratings of the importance and perfor-

mance of CESs by type. The overall importance of CESs to all the visitors (24.88) was lower than their performance level (78.97). The satisfaction with recreation and cultural heritage was significantly higher than the other service categories, and the emphasis on aesthetic experiences and recreation was significantly higher than the other service categories. The IPA perception evaluation model was used to analyze the performance of different categories of CESs and the visitors' emphasis. The IPA analysis uses the average values of importance and satisfaction as the dividing points for the X–Y axis, dividing the space into four quadrants [54], corresponding to different management priorities: the first quadrant represents high importance–high satisfaction; the second quadrant represents high importance–low satisfaction; the third quadrant represents low importance–low satisfaction; and the fourth quadrant represents low importance–high satisfaction. According to the perception evaluation model (Figure 6), the CESs provided by urban parks in Hangzhou's main urban area met visitors' needs well. The CES categories that could continue to be maintained include inspiration, existential values, science education, and social interaction; aesthetic experiences and recreation had significant advantages. Service categories that needed improvement included natural appreciation, spiritual services, and cultural heritage.

**Table 2.** Perceived performance and importance of cultural ecosystem services.

| CES Categories | Number of Negative Texts | Number of Active Texts | Importance | Performance (Satisfaction) |
|---|---|---|---|---|
| Spiritual services | 251 | 4868 | 17.37 | 51.00 |
| Aesthetic experiences | 399 | 7474 | 50.00 | 80.67 |
| Recreation | 691 | 9458 | 54.77 | 91.25 |
| Inspiration | 51 | 922 | 5.81 | 80.85 |
| Existential values | 42 | 1120 | 6.81 | 83.42 |
| Cultural heritage | 121 | 3098 | 18.76 | 77.46 |
| Science education | 110 | 2229 | 12.91 | 93.90 |
| Social interaction | 217 | 2807 | 17.79 | 81.74 |
| Natural appreciation | 496 | 7754 | 39.72 | 70.72 |
| Total | 2378 | 3,9730 | 24.88 | 78.97 |

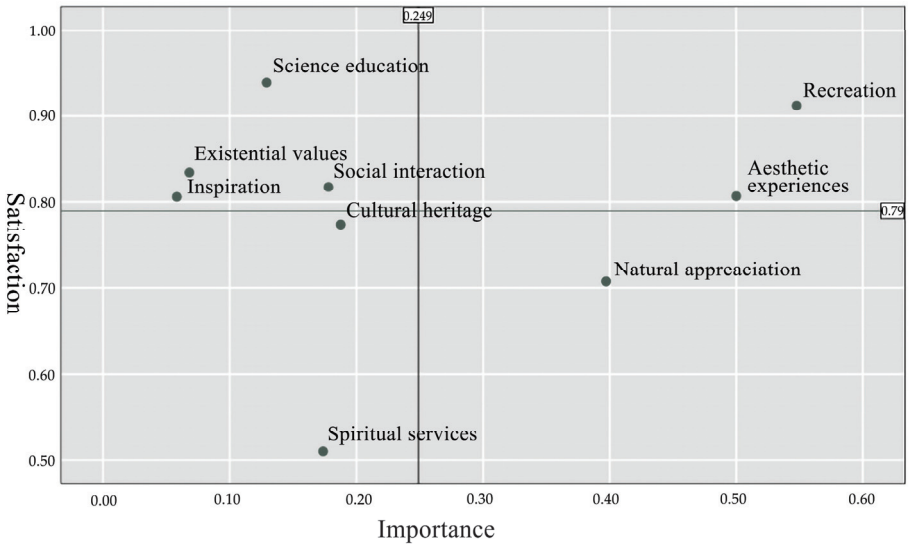



**Figure 6.** The importance and satisfaction of cultural ecosystem service perception.

### *3.2. Landscape Factors in Social Media Photos*

After iterative training, the YOLO v5 model had an average precision of 0.981, demonstrating exemplary performance in annotating target images. In verifying 1122 manually annotated images against the model results, all 21 landscape factors showed high precision and recall rates (Table 3). The YOLO v5 model identified landscape factors in 7662 pho-

tos out of 14,752 pieces of metadata (excluding data where a CES was not recognized). Among the identified landscape factors, biological landscape had the highest frequency (61.00%, $n$ = 6795), followed by hydrological landscape (16.58%, $n$ = 1847) and architectural landscape (15.89%, $n$ = 1770). The lowest frequency in the 7662 photos was for facility landscape (6.53%, $n$ = 727). As each Weibo post might encode multiple CES categories, we used the Python programming language to match each CES type with landscape factors for each piece of data, resulting in 32,874 corresponding data entries. Among them, biological landscape were associated with the most perceived CESs ($n$ = 17,769), while the fewest were found in facility landscape ($n$ = 2629) (Table 4). After visualizing Table 4 (Figure 7), we learned that among the four categories of landscapes, hydrological and biological landscape mainly provided perceptions of spiritual services, aesthetic experiences, and recreation. The natural appreciation function was more reflected in biological landscape, while the cultural heritage and recreation functions tended to be reflected in architectural and facility landscape.

**Table 3.** Image annotation results and accuracy.

| Landscape Categories | Landscape Factors | Number of Labels | Accuracy | Recall | mAP@0.5 | mAP@[0.5 = 0.95] |
|---|---|---|---|---|---|---|
| Hydrological landscape | Lakes | 112 | 0.991 | 0.953 | 0.994 | 0.826 |
| | Ponds | 163 | 0.918 | 0.660 | 0.985 | 0.747 |
| | Natural revetments | 263 | 0.890 | 0.889 | 0.952 | 0.626 |
| Biological landscape | Arbors | 438 | 0.961 | 0.947 | 0.985 | 0.790 |
| | Lawns | 69 | 0.985 | 0.927 | 0.983 | 0.769 |
| | Herbaceous flowers | 321 | 0.970 | 0.984 | 0.993 | 0.813 |
| | Woody flowers | 178 | 0.966 | 1.000 | 0.933 | 0.841 |
| | Groves | 99 | 0.980 | 0.878 | 0.988 | 0.730 |
| | Fish | 114 | 0.923 | 0.982 | 0.990 | 0.773 |
| | Birds | 77 | 0.991 | 1.000 | 0.995 | 0.712 |
| | Other animals | 227 | 0.980 | 1.000 | 0.995 | 0.841 |
| Architecture landscape | Pavilions | 26 | 0.785 | 1.000 | 0.978 | 0.808 |
| | Bridges | 70 | 0.975 | 0.971 | 0.986 | 0.768 |
| | Towers | 27 | 0.836 | 0.941 | 0.955 | 0.611 |
| | Other traditional buildings | 220 | 0.949 | 0.986 | 0.993 | 0.778 |
| | Modern architecture | 81 | 0.947 | 1.000 | 0.993 | 0.842 |
| Facility landscape | Entertainment facilities | 127 | 0.965 | 1.000 | 0.994 | 0.811 |
| | Identification facilities | 47 | 0.994 | 1.000 | 0.995 | 0.876 |
| | Seats | 40 | 1.000 | 0.966 | 0.989 | 0.754 |
| | Landscape sketches | 52 | 0.949 | 1.000 | 0.995 | 0.855 |
| | Roads | 110 | 0.956 | 0.982 | 0.994 | 0.789 |

**Table 4.** The occurrence frequency and proportion of CES categories in different landscape categories.

| CES Categories | Hydrological Landscape | | Biological Landscape | | Architecture Landscape | | Facility Landscape | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | N | % | N | % | N | % | N | % | N |
| Spiritual services | 1208 | 3.83 | 3199 | 10.13 | 499 | 1.58 | 318 | 1.01 | 5224 |
| Aesthetic experiences | 1179 | 3.73 | 3455 | 10.94 | 957 | 3.03 | 188 | 0.60 | 5779 |
| Recreation | 984 | 3.12 | 3777 | 11.96 | 799 | 2.53 | 697 | 2.21 | 6257 |
| Inspiration | 180 | 0.57 | 427 | 1.35 | 144 | 0.46 | 129 | 0.41 | 880 |
| Existential values | 146 | 0.46 | 500 | 1.58 | 540 | 1.71 | 150 | 0.48 | 1336 |
| Cultural heritage | 231 | 0.73 | 620 | 1.96 | 1535 | 4.86 | 213 | 0.67 | 2599 |
| Science education | 234 | 0.74 | 575 | 1.82 | 655 | 2.07 | 314 | 0.99 | 1778 |
| Social interaction | 194 | 0.61 | 579 | 1.83 | 368 | 1.17 | 413 | 1.31 | 1554 |
| Natural appreciation | 721 | 2.28 | 4637 | 14.69 | 604 | 1.91 | 207 | 0.66 | 6169 |
| Total | 5077 | 16.08 | 17,769 | 56.27 | 6101 | 19.32 | 2629 | 8.33 | 31,576 |

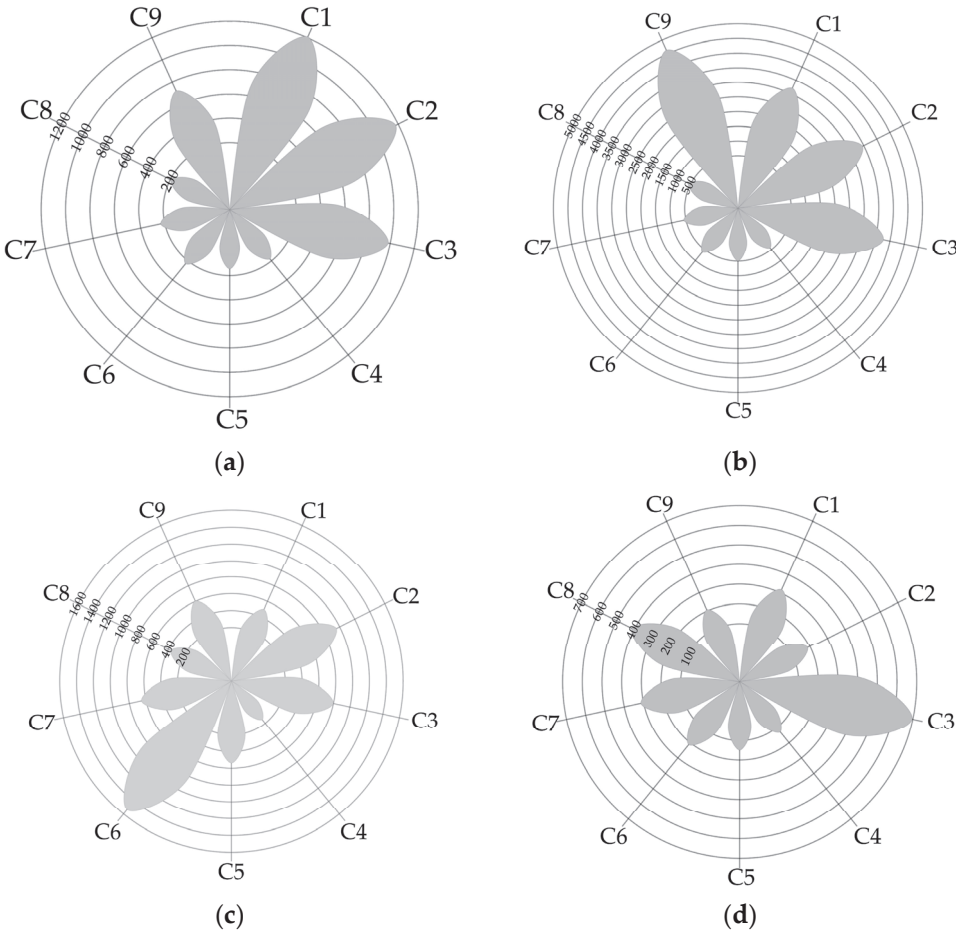



**Figure 7.** Heterogeneity of CES categories under landscape categories. (**a**) Hydrological landscape; (**b**) biological landscape; (**c**) architecture landscape; (**d**) facility landscape; C1: spiritual services; C2: aesthetic experiences; C3: recreation; C4: inspiration; C5: eexistential values; C6: cultural heritage; C7: science education; C8: social interaction; C9: natural appreciation.

### *3.3. The Correlation between Urban Park CESs and Landscape Factors*

#### 3.3.1. Interconnectedness of CES Categories in Urban Parks

Through the Apriori association rule analysis of visitors' perceptions of CES categories, 11 association rules that met the conditions (confidence > 60.00% and conditional support > 20.00%) were mined (as shown in Table 5). These 11 association rules indicated strong correlations with a temporal sequence. The most frequent itemsets included aesthetic experiences (C2)–recreation (C3), spiritual services (C1)–aesthetic experiences (C2), and spiritual services (C1)–recreation (C3). This result indicated that in the context of 25 urban parks, these three CES categories were frequently perceived together and had solid correlations and orders. As seen from Table 5, when women perceived aesthetic experiences or spiritual services in urban parks, they were highly likely to perceive recreation. Rules 7–11 reflected the association rules between four categories, and there was a high probability of perceiving another type when perceiving spiritual services with aesthetic experiences or recreation.

We conducted a Spearman correlation analysis to demonstrate the overall correlation among all the CES categories. As seen in Figure 8, there was a correlation among the CES categories, and they exhibited varying degrees of correlation. In addition to the three pairs C1–C2, C1–C3, and C2–C3 with high correlations ($R > 0.85$), the correlation between natural appreciation and aesthetic experiences, recreation, and spiritual services was also high, with $R$ values of 0.93, 0.88, and 0.83, respectively. Additionally, the correlation between recreation and social interaction also reached 0.83. However, we found two negative correlations: existential values and inspiration ($R = -0.07$) and inspiration and science

education ($R$ = 0.00). This finding suggested that when visitors perceive existential values or scientific education, their perception of inspiration might weaken.

**Table 5.** Mining table for association rules between categories of cultural ecosystem services.

| Number | X | Y | Number of Instances | Support Percentage | Confidence Percentage | Rule Support Percentage | Lift |
|---|---|---|---|---|---|---|---|
| 1 | C2 | C3 | 7825 | 45.32 | 60.79 | 27.55 | 1.12 |
| 2 | C1 | C2 | 5914 | 34.25 | 63.22 | 21.66 | 1.40 |
| 3 | C1 | C3 | 5914 | 34.25 | 68.28 | 23.39 | 1.26 |
| 4 | C2,0 | C3 | 5232 | 30.30 | 61.70 | 18.70 | 1.14 |
| 5 | C1,0 | C2 | 4225 | 24.47 | 61.40 | 15.02 | 1.35 |
| 6 | C1,0 | C3 | 4225 | 24.47 | 68.17 | 16.68 | 1.26 |
| 7 | C9,C2 | C3 | 4055 | 23.49 | 63.87 | 15.00 | 1.18 |
| 8 | C1,C3 | C2 | 4038 | 23.39 | 66.86 | 15.64 | 1.48 |
| 9 | C9,C3 | C2 | 3874 | 22.44 | 66.86 | 15.00 | 1.48 |
| 10 | C1,C2 | C9 | 3739 | 21.66 | 60.76 | 13.16 | 1.53 |
| 11 | C1,C2 | C3 | 3739 | 21.66 | 72.21 | 15.64 | 1.34 |

Note: 0 is female; C1 is spiritual services; C2 is aesthetic experiences; C3 is recreation; C9 is natural appreciation.

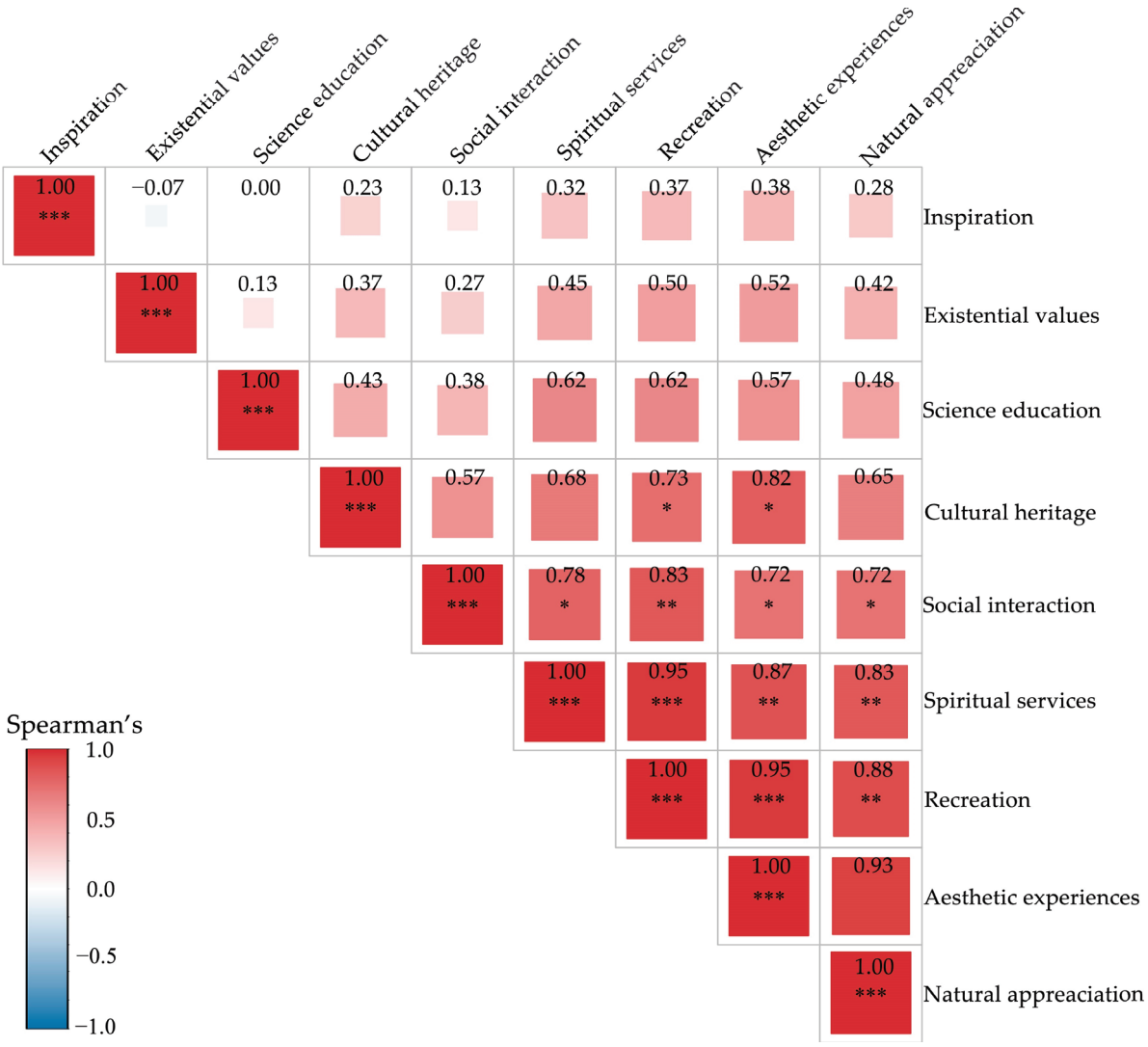



**Figure 8.** Correlation between categories of cultural ecosystem services. Note: ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$.

3.3.2. Correlation between CES Categories and Park Landscape Factors

Cross-tabulation and Monte Carlo post hoc chi-square tests showed a significant statistical correlation between the CES categories and landscape factors ($\chi^2$ = 21,156.983, df = 160, $p < 0.05$). We used an MCA analysis and the Euclidean distance measurement method to associate landscape factors in photos with CES categories in text data. The results of the analysis showed that three components account for 39.11% of the total variance in visitors' expression of perceived CES categories (Figure 9 shows the dual plots of the first two axes). The first part of Figure 9 (accounting for 52.39% of the total variance) revealed gender differences in visitor perception. Component 2 (accounting for 48.58% of the total variance) showed the perceived connection between landscape factors and cultural ecosystem service categories.

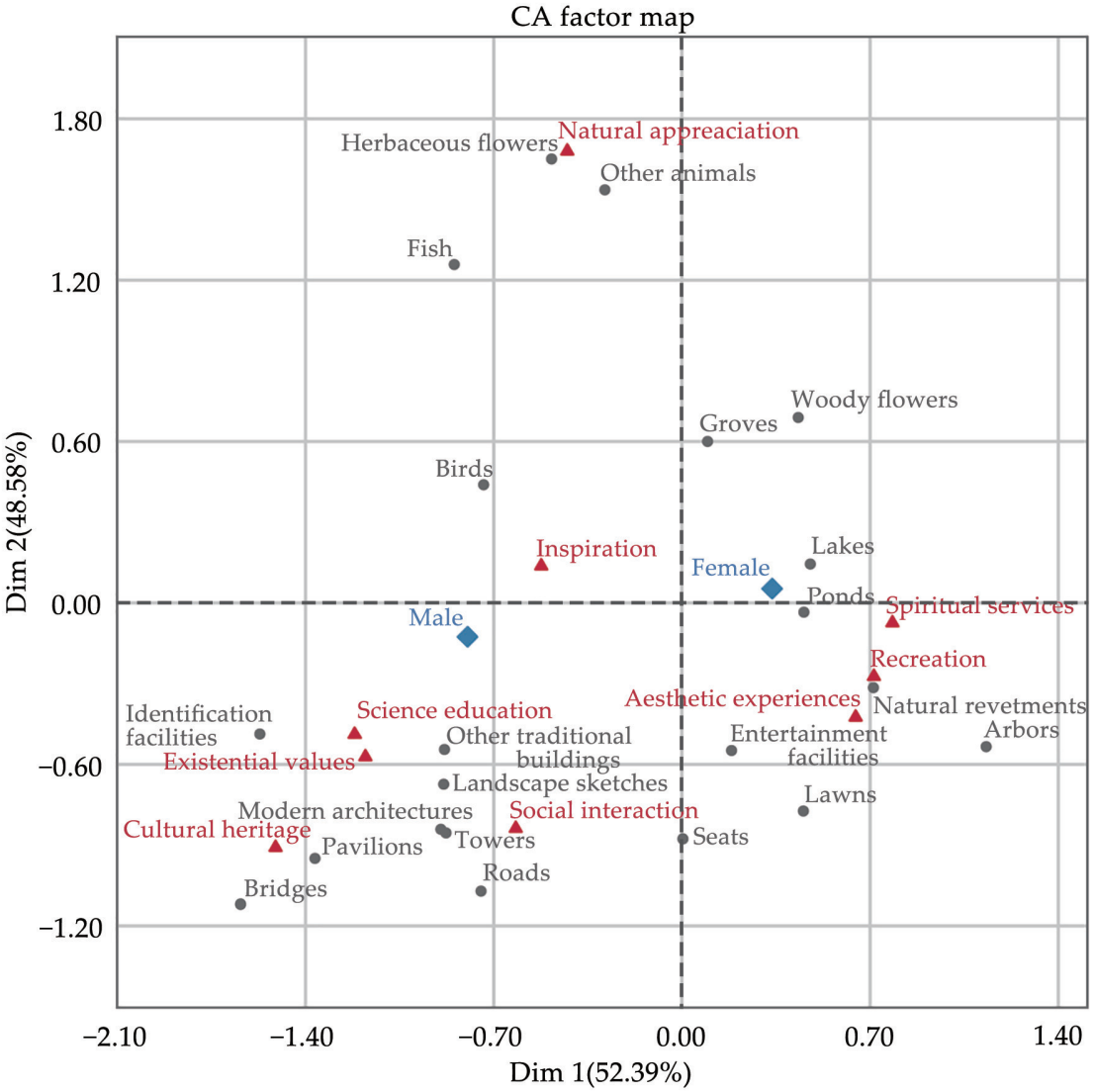



**Figure 9.** The MCA diagram shows the positions of CESs (red font), landscape factors (gray font), and visitor gender (blue font) in the first two-dimensional factor plan.

The MCA indicated that user gender, landscape factors, and perceived CES categories were closely related. Concerning gender landscape preferences, males and females were in the third and first quadrants, respectively, with some differences. Males preferred architectural landscapes (other traditional buildings, modern buildings, pavilions, bridges, towers), landscape sketches, identification facilities, and roads. At the same time, females were more inclined to perceive hydrological landscapes (lakes, ponds, natural revetments),

groves, and woody flowers. Regarding CES categories, males had a higher perception of science education, existential values, cultural heritage, and inspiration, while females were likelier to perceive recreation, aesthetic experiences, and spiritual services. In studying the correlation between CESs and landscape factor perception, we could judge the degree of correlation based on the distance to the origin [55]. From the MCA dual-line chart (Figure 9), we found that natural appreciation was closely related to herbaceous flowers, other animals, and fish, showing a significant correlation. Recreation, spiritual services, and aesthetic experiences form a bundle closely related to ponds, natural revetments, lawns, and groves. Additionally, science education, existential values, and cultural heritage form another bundle associated with identification facilities, landscape sketches, and architectural landscapes (other traditional buildings, modern buildings, pavilions, towers, and bridges). Pavilions and bridges were closely connected to historical and cultural factors, while towers, modern architecture, and roads were closely linked to social interaction. Traditional buildings and signage facilities were closely associated with science education and existential values.

The author created a Sankey diagram to visually represent each CES category's perceptual flow. As shown in Figure 10, females contributed significantly to the perception of all the CES categories, enhancing the perceptions of spiritual services, aesthetic experiences, and recreation for all landscape factors, particularly arbors and herbaceous flowers, fish, landscape sketches, and seats, which had the lowest contribution rates to the perceptions of the remaining six CES categories.

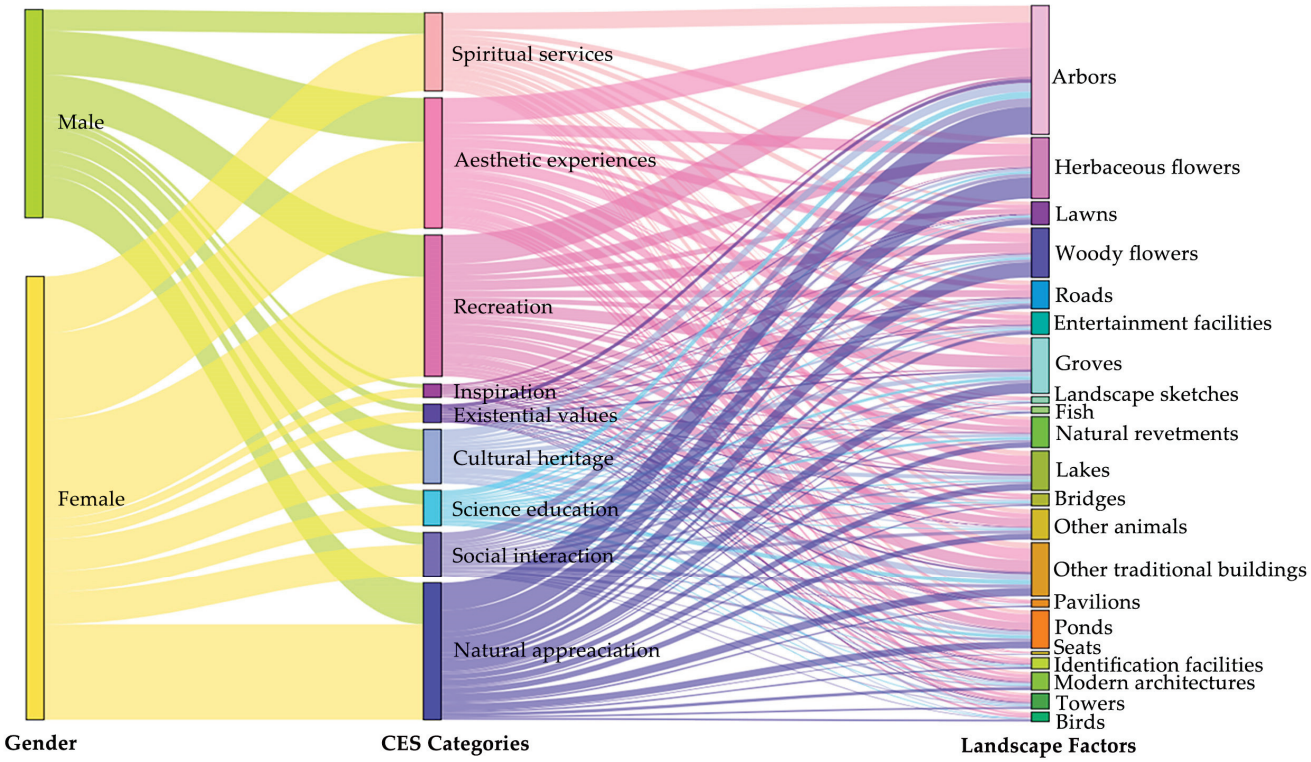



**Figure 10.** Cultural ecosystem services and landscape factors, gender relationship flow.

## 4. Discussion

### *4.1. Visitors' Preferences for Cultural Ecosystem Service Categories and Landscape Factors in Parks*

In previously published studies, visitors' perceptions of CESs, entertainment, and aesthetics have often been highlighted, while capturing inspiration was less common [24,56]. These research results partially aligned with our findings. Through using NLP methods to identify comments, we found that the overall perception frequency of Hangzhou urban parks' CESs was relatively high. Among them, spiritual services, aesthetic experiences, recreation, and natural appreciation were most easily perceived by the public. At the

same time, inspiration and existential values were relatively challenging to perceive. This phenomenon was related to Hangzhou being one of China's famous historical and cultural cities and tourist destinations. Yao and Leng et al. [57] found that parks with high-level management, service environments, and green coverage could bring residents pleasant mental experiences. In contrast to the results of Gai et al. [3], this research found that visitors' overall perception of the importance of CESs was lower than their actual performance. This result was related to the high-quality construction and service management of urban parks in Hangzhou. According to the IPA analysis, visitors had higher expectations for natural appreciation, spiritual services, and cultural heritage, but the actual performance of parks in these aspects was slightly lower. This phenomenon might be attributed to factors such as a high prevalence of mosquitoes in the plant community and a lack of systematic introduction and interpretation of historic and cultural landscapes in the parks. In future urban park construction and management, in addition to introducing mosquito-repelling plants in close-range viewing areas, using innovative educational methods such as WeChat accounts for dissemination and QR code technology to share information about flora and historical buildings can also enhance visitor satisfaction with natural appreciation, science education, and cultural heritage.

According to the statistics of 17,266 user–day (PUD) photos, three landscape factors, including arbors (19.01%), herbaceous flowers (8.99%), and groves (8.22%), were more frequently depicted in landscape factors. This was consistent with the findings of Oteros-Rozas et al. [26], Ma et al. [45], and Graves et al. [58], who found that the public highly perceived plant landscapes such as trees. The degree of preference for different landscape factors was similar to the conclusion of Huang et al. [59], who found that the preferred landscape factors in urban parks were deciduous trees > herbaceous flowers > ponds > gates > pavilions. Daniel et al. [60] found that over 20.00% of photos were taken of nature, and natural photos were more likely to occur in parks and areas with high vegetation cover. Similar to this discovery, we also extracted a relatively high proportion of natural landscapes from the photo data. At the same time, unlike the conclusion of Yang et al. [61], there were some differences in landscape category preferences based on visitor gender. Males preferred architectural landscapes, facility landscapes, and roads. At the same time, females were more inclined to perceive hydrological landscapes, groves, and woody flowers. This difference might be related to gender habits. Yang et al. [62] found that most male tourists preferred sitting, while female tourists preferred taking photographs. In Hangzhou, urban parks, flower clusters, and natural embankments often attract visitors to pause and take pictures. Urban park managers can capitalize on gender-specific landscape preferences by strategically placing service facilities in different recreational areas. For instance, they can create prominent photo spots in flower landscapes favored by women and install nearby restroom facilities to enhance the visitor experience.

### *4.2. Factors Influencing Visitors' Perception of Cultural Ecosystem Services in Park Landscapes*

The research indicated that a set of ecosystem service functions can consistently co-occur in time and space and could be perceived concurrently. This aligned with conclusions from studies by Jang et al. [35], Zhai et al. [63], and Wang et al. [64]. The Apriori association rule analysis revealed a significant correlation between aesthetic experiences, recreation, and spiritual services. This result resembled the conclusion that nature-based tourism affects visitors' happiness [65]. Unlike Fulvia et al. [34], a strong association was found between natural appreciation, aesthetic experiences, and recreation. When users perceived natural appreciation and recreation, there was a high probability of perceiving aesthetic experiences. This might be due to the introduction of flowering plants or trees species in urban parks, which enhanced park attractiveness and conveyed aesthetic experiences [22]. Previous research on demographic characteristics and CESs found gender to be a crucial factor influencing public perception [66]. This study found females were more likely to perceive CESs than males, contrasting with Tan et al. [67] but aligning with Calvet-Mir et al. [68]. Exploring the preference differences in CES categories, females preferred

aesthetic experiences, recreation, and spiritual services, while males preferred cultural heritage, science education, existential values, and social interaction. Researchers drew divergent conclusions about gender preferences [33,69], which might be influenced by age, occupation, cultural differences, etc.

In this study, an MCA analysis was used to bind CES categories with landscape factors, revealing a close relationship between landscape factors and CES category perception. Previous research [23,43] found that all 21 landscape factors influenced CES category perception to varying degrees, and the same landscape factor could influence multiple CES categories. Among them, the main factors influencing CESs were arbors, herbaceous flowers, woody flowers, other traditional buildings, natural revetments, towers, landscape sketches, bridges, and other animals. Numerous studies have demonstrated these landscape factors to be generally preferred by the public [45,70,71]. Overall, associations formed three bundles of CES and landscape factors. As expected, the perception of natural appreciation mainly came from natural landscapes (biological and water). These landscape factors often coexist because environments such as lakes and forests are habitats for various animals. Similar to the findings of Zhang et al. [23], natural areas did not have a significant advantage in contributing to their existential values compared to non-natural areas such as landscape sketches, buildings, roads, and identification facilities. Science education, cultural heritage, and social interaction often trigger perceptions related to human-made landscapes [26]. Regrettably, we found that visitors' perception of science education was mainly related to artificial landscapes, such as identification facilities, and they rarely paid attention to the knowledge provided by natural factors, such as plants in urban parks. The perception of cultural heritage came mainly from landscape factors such as identification facilities and buildings (pavilions, bridges, towers, and modern buildings). These landscapes were usually carriers of poetry and scientific texts. Some identification facilities recorded information about plants and structures, while certain buildings were endowed with personified historical images and spiritual representations [28]. Visitors intuitively perceived these landscape factors as historical and cultural, and they were also considered to have good educational and scientific uses [72]. At urban life's brisk pace, few tourists felt the urge to explore historical knowledge, except for professionals. Urban park staff can strengthen science education by promoting experiential learning through practice, such as knowledge tests and architectural pattern design competitions, to enhance their understanding of architecture and biological landscapes through participatory activities. In the third bundling group, landscapes contributing to recreation, aesthetic experiences, and mental satisfaction shared similarities. These similarities primarily came from hydrological features and vegetation, including natural revetments, ponds, lawns, and arbors. Similar studies have also extensively reported on the importance of vegetation and water bodies for aesthetics [73,74]. As suggested by Zhang et al. [75], planting more trees and vibrant flowers and providing transparent water sources could enhance public aesthetics and improve mental restoration.

### *4.3. Methodological Advantages and Limitations*

In recent years, social media data have become a new trend in researching CESs. Compared to traditional data, social media text data have the advantages of a large volume, long span, accessible collection, and strong randomness [17] and have gradually become an important data source for studying CES perception. This study combined text data with photo data and used machine learning to advance more accurate photo content recognition. This process overcame the limitation that a single type of data might cause the public to lose some perceptual information. Li et al. [76] focused on analyzing the text and image data of Weibo and proved that these two types of data can comprehensively describe public aesthetic elements. Landscape studies have indicated that this method could effectively reflect users' perceptions of CESs and landscape factors [20]. Furthermore, by assessing CES and landscape factor perceptions, we can comprehensively understand

human interactions in urban parks [3], providing decision makers with more targeted transformation suggestions and a theoretical basis.

While this study proposed a method for combined text and image CES research, it had limitations related to online data. Uploaded data content is influenced by visitor characteristics like education level, gender, income, and visit frequency. Obtaining such data is challenging on privacy-focused social media platforms, reflecting the current state of most platforms [17,24]. Social media data mainly reflect the opinions of younger users who publish comments, making it challenging to study the perceptions of users like children and the elderly who do not often comment. Future research could employ various methods, including surveys, participatory mapping, and social media evaluation for different user groups. Integrating multiple data sources, including mobile signaling and exercise app data [17], can enhance CES perception evaluation methods. Refining factors influencing public CES perception will provide park managers with practical suggestions for improving CES supply and spatial quality in urban parks.

## 5. Conclusions

Cultural ecosystem services do not represent the quality of the ecological environment but rather reflect the complex and dynamic interactions between ecosystems and humans. This study analyzed park visitors' preferences for CESs provided by urban parks and the impact of landscapes on these preferences from a first-person perspective. We found that utilizing two types of data from the Weibo platform to explore visitors' perceptions of CESs and landscape factors was an effective method. In addition to different association rules within CES categories, the perception of CES categorieswas also closely correlated with visitor gender and landscape factors. This correlation led to bundling multiple landscape factors with several CES categories. To improve the quality of park ecological services and meet the needs of residents, the construction and management of urban parks should carefully consider the preferences of park visitors towards CES and landscapes. Detailed landscape factors can be employed to target improvements in specific CES categories. However, due to the limitations of the social media user population, the research cannot deeply understand the influence of personal information factors. In subsequent steps, a combination of participatory mapping and various data types, such as mobile signaling, should be employed for a broader analysis to enhance the practical significance of the research results.

**Author Contributions:** Conceptualization, Y.C., Y.Z. and F.S.; methodology, Y.C.; software, Y.C.; validation, Y.C. and Y.Y.; formal analysis, Y.C.; investigation, Y.C., C.H., Y.Y., J.L., Y.W. and T.Z.; resources, Y.C. and C.H.; data curation, Y.C. and C.H.; writing—original draft preparation, Y.C.; writing—review and editing, Y.C.; visualization, Y.C., C.H. and Y.Y.; supervision, Y.Z. and F.S.; project administration, Y.Z. and F.S.; funding acquisition, F.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Key R&D Program of China, grant number: 2022YFF1303102.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy reasons.

**Acknowledgments:** We thank Cong Zhang and Juan Yao for their valuable comments and suggestions on the manuscript. We also express our gratitude to Shanghai Tengyun Biotechnology Co., Ltd. for developing the Hiplot Pro platform and providing technical assistance and valuable tools for the data analysis and visualization.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Appendix A

**Table A1.** Detailed information on 25 city parks.

| District | Urban Park Name | Area/hm$^2$ | Types | Number of Valid Comments |
|---|---|---|---|---|
| Xihu District | The Prince Bay Park | 80.00 | Comprehensive park | 2497 |
| | Viewing Fish at Flower Pool Park | 20.00 | Comprehensive park | 1548 |
| | Breeze-ruffled Lotus at Quyuan Garden | 12.65 | Comprehensive park | 1901 |
| | Hupao Park | 13.12 | Other specialized park (theme of Tiger Running Spring) | 619 |
| | HangZhou Zoo | 20.00 | Specialized park (zoo) | 2195 |
| | HangZhou Botanical Park | 284.64 | Specialized park (botanical park) | 2991 |
| | Youth & Children's Park | 14.00 | Other specialized park (children's park) | 81 |
| | Agoda of Six Harmonies Park | 6.80 | Specialized park (heritage park) | 108 |
| | Xishan Forest Park | 1381.00 | Other specialized park (urban forest park) | 52 |
| | Wuchao Mountain Forest Park | 522.00 | Other specialized park (urban forest park) | 47 |
| | Tongjian Lake Park | 67.72 | Other specialized park (urban wetland park) | 59 |
| | The Xixi National Westland Park | 1150 | Other specialized park (urban wetland park) | 1026 |
| Shangcheng District | White Pagoda Park | 78.40 | Comprehensive park | 2246 |
| | Chengdong Park | 6.26 | Comprehensive park | 69 |
| | Orioles Singing in the Willow | 21.00 | Comprehensive park | 510 |
| | Bachelor Park | 12.70 | Comprehensive park | 68 |
| | Chengbei Sports Park | 44.78 | Other specialized park (sports and gymnastic park) | 52 |
| | Jiangyangfan Ecological Park | 19.80 | Other specialized park (urban wetland park) | 56 |
| | Long bridge Park | 2.80 | Other specialized park (waterfront park) | 203 |
| | The Eight Diagrams Field Heritage Park | 6.00 | Specialized park (heritage park) | 435 |
| | Lakeside Park | 5.80 | Other specialized park (waterfront park) | 53 |
| | Yongjin Park | 2.80 | Other specialized park (waterfront park) | 53 |
| Gongshu District | Grand Canal Asian Games Park | 46.70 | Comprehensive park | 33 |
| | Banshan Forest Park | 1002.88 | Other specialized park (urban forest park) | 257 |
| Binjiang District | Riverside Park | 28.00 | Comprehensive park | 107 |

Although the area of Chengdong Park does not exceed 10 hm$^2$, it is stated in the government announcement that it is a comprehensive park. (https://wgly.hangzhou.gov.cn/art/2022/1/17/art_1229505585_58939557.html, accessed on 12 December 2022).

## References


1. Huai, S.Y.; Voorde, T.V.D. Which environmental features contribute to positive and negative perceptions of urban parks? A cross-cultural comparison using online reviews and natural language processing methods. *Landsc. Urban Plan.* **2022**, *218*, 104307. [CrossRef]
2. Gao, W.; Wang, S.Y.; Chen, S.T.; Hu, S.J.; Li, H. Identifying cultural ecosystem services and relevant landscape elements provided by urban green space throughout history from an information communication perspective. *Forests* **2023**, *14*, 1045. [CrossRef]
3. Gai, S.J.; Fu, J.M.; Rong, X.; Dai, L.L. Users' views on cultural ecosystem services of urban parks: An importance-performance analysis of a case in Beijing, China. *Anthropocene* **2022**, *37*, 100323. [CrossRef]
4. Kabisch, N.; Qureshi, S.; Haase, D. Human-environment interactions in urban green spaces—A systematic review of contemporary issues and prospects for future research. *Environ. Impact Asses.* **2015**, *50*, 25–34. [CrossRef]
5. Millennium ecosystem assessment. In *Ecosystems and Human Well-Being: Synthesis*; Island Press: Washington, DC, USA, 2005; Volume 2022, pp. 26–101. Available online: https://www.millenniumassessment.org/documents/document.356.aspx.pdf (accessed on 5 January 2023).
6. Dade, M.C.; Mitchell, M.G.E.; Brown, G.; Rhodes, J.R. The effects of urban greenspace characteristics and socio-demographics vary among cultural ecosystem services. *Urban For. Urban Green.* **2020**, *49*, 126641. [CrossRef]
7. Zhang, Y.; Qiu, H.F. A study on public perception of Cultural ecosystem services in lake parks based on latent Dirichlet Allocation Model. *Chin. Landsc. Archit.* **2023**, *39*, 121–126. [CrossRef]
8. Andersson, E.; Tengö, M.; McPhearson, T.; Kremer, P. Cultural ecosystem services as a gateway for improving urban sustainability. *Ecosyst. Serv.* **2015**, *12*, 165–168. [CrossRef]
9. Huai, S.Y.; Chen, F.; Liu, S.; Canters, F.; Voorde, T.V.D. Using social media photos and computer vision to assess cultural ecosystem services and landscape features in urban parks. *Ecosyst. Serv.* **2022**, *57*, 101475. [CrossRef]
10. Dickinson, D.C.; Hobbs, R.J. Cultural ecosystem services: Characteristics, challenges and lessons for urban green space research. *Ecosyst. Serv.* **2017**, *25*, 179–194. [CrossRef]
11. Zuo, Y.L.; Chang, J.; Liu, W. Evaluation of cultural ecosystems services of urban park from the perspective of tourists: A case study of DaMing lake park in Jinan. *J. Guilin Univ. Technol.* 2023. *in press*. Available online: https://kns-cnki-net.webvpn.zafu.edu.cn/kcms/detail/45.1375.N.20230927.1928.002.html (accessed on 14 January 2024).
12. Yang, L.J.; Cao, K.J. Cultural ecosystem services research progress and future prospects: A review. *Sustainability* **2022**, *14*, 11845. [CrossRef]
13. Depietri, Y.; Ghermandi, A.; Campisi-Pinto, S.; Orenstein, D.E. Public participation GIS versus geolocated social media data to assess urban cultural ecosystem services: Instances of complementarity. *Ecosyst. Serv.* **2021**, *50*, 101277. [CrossRef]
14. Luo, Y.Y.; Xu, H.L.; Zhang, J.J.; Chen, N.; Ye, H.Y.; Lei, W.Y. Magnifier or refractor? Exploring the impact of geographical indication on people's perception of the value of cultural ecosystem services based on the SolVES model. *Front. Ecol. Evol.* **2023**, *11*, 1208169. [CrossRef]
15. Ruiz-Frau, A.; Ospina-Alvarez, A.; Villasante, S.; Pita, P.; Maya-Jariego, I.; Juan, S.D. Using graph theory and social media data to assess cultural ecosystem services in coastal areas: Method development and application. *Ecosyst. Serv.* **2020**, *45*, 101176. [CrossRef]
16. Wang, W.; Wu, C.Y.; Fang, Q.H.; Harrison, O.I. Cultural ecosystem services evaluation in a coastal city of China using social media data. *Ocean Coast. Manag.* **2023**, *242*, 106693. [CrossRef]
17. Dai, P.C.; Zhang, S.L.; Chen, Z.X.; Gong, Y.L.; Hou, H.P. Perceptions of cultural ecosystem services in urban parks based on social network data. *Sustainability* **2019**, *11*, 5386. [CrossRef]
18. Lee, H.; Seo, B.; Koellner, T.; Lautenbach, S. Mapping cultural ecosystem services 2.0—Potential and shortcomings from unlabeled crowd sourced images. *Ecol. Indic.* **2019**, *96*, 505–515. [CrossRef]
19. Richards, D.R.; Friess, D.A. A rapid indicator of cultural ecosystem service usage at a fine spatial scale: Content analysis of social media photographs. *Ecol. Indic.* **2015**, *53*, 187–195. [CrossRef]
20. Fox, N.; Graham, L.G.; Eigenbrod, F.; Bullock, J.M.; Parks, K.E. Enriching social media data allows a more robust representation of cultural ecosystem services. *Ecosyst. Serv.* **2021**, *50*, 101328. [CrossRef]
21. Chen, Y.; Caesemaecker, C.; Rahman, H.T.; Sherren, K. Comparing cultural ecosystem service delivery in dykelands and marshes using Instagram: A case of the Cornwallis (Jijuktu'kwejk) River, Nova Scotia, Canada. *Ocean Coast. Manag.* **2020**, *193*, 105254. [CrossRef]
22. Gugulica, M.; Burghardt, D. Mapping indicators of cultural ecosystem services use in urban green spaces based on text classification of geosocial media data. *Ecosyst. Serv.* **2023**, *60*, 101508. [CrossRef]
23. Zhang, K.L.; Tang, X.H.; Zhao, Y.T.; Huang, B.W.; Huang, L.J.; Liu, M.Y.; Luo, E.; Li, Y.X.; Jiang, T.; Zhang, L.Q.; et al. Differing perceptions of the youth and the elderly regarding cultural ecosystem services in urban parks: An exploration of the tour experience. *Sci. Total Environ.* **2022**, *821*, 153388. [CrossRef] [PubMed]
24. Guo, R.Z.; Lin, L.; Xu, J.F.; Dai, W.H.; Song, Y.B.; Dong, M. Spatio-temporal characteristics of cultural ecosystem services and their relations to landscape factors in Hangzhou Xixi National Wetland Park, China. *Ecol. Indic.* **2023**, *154*, 110910. [CrossRef]
25. Zoderer, B.M.; Stanghellini, P.S.L.; Tasser, E.; Walde, J.; Wieser, H.; Tappeiner, U. Exploring socio-cultural values of ecosystem service categories in the Central Alps: The influence of socio-demographic factors and landscape type. *Reg. Environ. Chang.* **2016**, *16*, 2033–2044. [CrossRef]

26. Oteros-Rozas, E.; Martín-López, B.; Fagerholm, N.; Bieling, C.; Plieninger, T. Using social media photos to explore the relation between cultural ecosystem services and landscape features across five European sites. *Ecol. Indic.* **2018**, *94*, 74–86. [CrossRef]
27. Zhang, G.C.; Yang, J.; Wu, G.W.; Hu, X.P. Exploring the interactive influence on landscape preference from multiple visual attributes: Openness, richness, order, and depth. *Urban For. Urban Green.* **2021**, *65*, 127363. [CrossRef]
28. Zhang, K.L. Study on the Evaluation of Urban Park Cultural Ecosystem Services and the Association with Landscape Elements Based on the Perception Difference of the Youth and the Elderly. Master's Thesis, Sichuan Agricultural University, Dujiangyan, China, June 2022. [CrossRef]
29. Valanszki, I.; Kristensen, L.S.; Jombach, S.; Ladanyi, M.; Kovacs, K.F.; Fekete, A. Assessing relations between cultural ecosystem services, physical landscape features and accessibility in Central-Eastern Europe: A PPGIS empirical study from Hungary. *Sustainability* **2022**, *14*, 754. [CrossRef]
30. García-Palomares, J.C.; Guti'errez, J.; Mínguez, C. Identification of tourist hot spots based on social networks: A comparative analysis of European metropolises using photo-sharing services and GIS. *Appl. Geogr.* **2015**, *63*, 408–417. [CrossRef]
31. Schirpke, U.; Timmermann, F.; Tappeiner, U.; Tasser, E. Cultural ecosystem services of mountain regions: Modelling the aesthetic value. *Ecol. Indic.* **2016**, *69*, 78–90. [CrossRef]
32. Vaz, A.S.; Gonçalves, J.F.; Pereira, P.; Santarém, F.; Vicente, J.R.; Honrado, J.P. Earth observation and social media: Evaluating the spatiotemporal contribution of non-native trees to cultural ecosystem services. *Remote Sens. Environ.* **2019**, *230*, 111193. [CrossRef]
33. Zhou, L.L.; Guan, D.J.; Huang, X.Y.; Yuan, X.Z.; Zhang, M.J. Evaluation of the cultural ecosystem services of wetland park. *Ecol. Indic.* **2020**, *144*, 106286. [CrossRef]
34. Calcagni, F.; Batallé, J.N.; Baró, F.; Langemeyer, J. A tag is worth a thousand pictures: A framework for an empirically grounded typology of relational values through social media. *Ecosyst. Serv.* **2022**, *58*, 101495. [CrossRef]
35. Jiang, Q.Z.; Wang, G.X.; Ling, X.Y.; Liu, N. Research on the perception of cultural ecosystem services in urban parks via analyses of online comment data. *Landsc. Archit. Front.* **2022**, *10*, 32–51. [CrossRef]
36. Riechers, M.; Barkmann, J.; Tscharntke, T. Diverging perceptions by social groups on cultural ecosystem services provided by urban green. *Landscape Urban Plan.* **2018**, *175*, 161–168. [CrossRef]
37. Kabisch, N.; Haase, D. Green justice or just green? Provision of urban green spaces in Berlin, Germany. *Landsc. Urban Plan.* **2014**, *122*, 129–139. [CrossRef]
38. Shi, W.W.; Mahdzar, S.S.S.; Li, W.C. Park inclusive design index as a systematic evaluation framework to improve inclusive urban park uses: The case of Hangzhou urban parks. *Appl. Sci.* **2023**, *13*, 12954. [CrossRef]
39. Yang, M.H.; Huang, X.J.; Song, T. A study on the evaluation of urban public space vitality based on "Explicit and implicit mutual learning": A case of park green space in Xi'an. *Hum. Geogr.* **2023**, *38*, 118–125+192. [CrossRef]
40. The common international classification of ecosystem services. In *Proposal for a Common International Classification of Ecosystem Goods and Services for Integrated Environmental and Economic Accounting*; European Environment Agency Press: Nottingham, UK, 2010; pp. 1–22. Available online: https://unstats.un.org/unsd/envaccounting/ceea/meetings/UNCEEA-5-7-Bk1.pdf (accessed on 10 January 2023).
41. Kumar, P. *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*, 1st ed.; Earthscan: London, UK, 2010; pp. 113–148. [CrossRef]
42. Gozalo, G.R.; Morillas, J.M.B.; González, D.M.; Moraga, P.A. Relationships among satisfaction, noise perception, and use of urban green spaces. *Sci. Total Environ.* **2018**, *624*, 438–450. [CrossRef]
43. Huang, W.; Lu, S.Z.; Guo, Y.Q. Measuring the perceived heterogeneity of cultural ecosystem services in national cultural parks: Evidence from China. *Sustainability* **2023**, *15*, 9428. [CrossRef]
44. Li, H.R.; Liu, Z.; Li, X.X.; Zheng, X. Evaluation of cultural ecosystem services in urban riverside green space based on online social media commentary. *J. Landsc. Archit.* **2023**, *30*, 80–88. [CrossRef]
45. Ma, X.Q. A Study on Landscape Image and Public Perception and Preferences of WuHan Lake Parks Based on Computer Vision Algorithm. Master's Thesis, Huazhong Agricultural University, Wuhan, China, June 2022. [CrossRef]
46. Booth, N.K. *Basic Elements of Landscape Architectural Design*, 1st ed.; Cao, L.K.; Cao, D.K., Translators; Beijing Science & Technology Press: Beijing, China, 2018; pp. 2–289.
47. Wang, Z.F.; Miao, Y.L.; Xu, M.; Zhu, Z.W.; Qureshi, S.; Chang, Q. Revealing the differences of urban parks' services to human wellbeing based upon social media data. *Urban For. Urban Green.* **2021**, *63*, 127233. [CrossRef]
48. Wang, G.X. The Perceived Impact of Urban Park Landscape Pattern on Cultural Services in Jinan City Based on Social Media Data. Master's Thesis, Shandong Jianzhu University, Jinan, China, June 2022. [CrossRef]
49. Yang, T.F.; Xie, J.B.; Song, P.L.; Li, G.Q.; Mou, N.X.; Gao, X.Y.; Zhao, J. Monitoring ecological conditions by remote sensing and social media data—Sanya city (China) as case study. *Remote Sens.* **2022**, *14*, 2824. [CrossRef]
50. Du, C.; Wang, X.; Dong, Z.H.; Wang, Y.L.; Jiang, Z.H. lmproved YOLO v5s flame and smoke detection method for underground garage. *Comput. Eng. Appl.* **2023**, in press. [CrossRef]
51. Adegun, A.A.; Dombeu, J.V.F.; Viriri, S.; Odindi, J. State-of-the-Art deep learning methods for objects detection in remote sensing satellite images. *Sensors* **2023**, *23*, 5849. [CrossRef] [PubMed]
52. Wang, W.T. Research on Lushan Mountain Landscape Image Recognition System Base on Improved YOLOv4. Master's Thesis, Nanjing University of Information Science and Technology, Nanjing, China, June 2022. [CrossRef]

53. Lin, P.; Chen, L.L.; Luo, Z.S. Analysis of tourism experience in Haizhu National Wetland Park based on web text. *Sustainability* **2022**, *14*, 3011. [CrossRef]
54. Wang, M.; Qiu, M.; Wang, J.Q.; Peng, Y. The supply-demand relation analysis and improvements based on importance-performance analysis of cultural ecosystem services in waterfront areas along the Suzhou creek in Shanghai. *Landsc. Archit.* **2019**, *26*, 107–112. [CrossRef]
55. Liu, F.Y.; Liu, X.Y.; Kang, Z.Y.; Dai, J.C. Study on the difference between projected and perceived images of ecological festivals: A case of Beijing International Horticultural Exposition 2019. *J. Chin. Ecotourism* **2022**, *12*, 704–717. [CrossRef]
56. Wang, Z.F.; Xu, M.; Lin, H.W.; Qureshi, S.; Cao, A.K.; Ma, Y.J. Understanding the dynamics and factors affecting cultural ecosystem services during urbanization through spatial pattern analysis and a mixed-methods approach. *J. Clean. Prod.* **2021**, *279*, 123422. [CrossRef]
57. Yao, X.S.; Leng, H. Study on satisfaction of park recreation space based on structural equation model: A case study of Changchun. *Archit. J.* **2017**, *64*, 32–37. Available online: https://kns-cnki-net-443.webvpn.zafu.edu.cn/kcms2/article/abstract?v=j6HAoO1nZAw5l4gp1jNPer7rTG0wvrhbWKxeinBgOs78OyvFOq8aP2ObiMZ4iG_AcGf5VPn2Ah5YlTwORRLWjAnprrg57m-yCM-tI6tiPWACOXyY_F6EcHFChPNUFNNk5Gks2WIyO-I=&uniplatform=NZKPT&language=CHS (accessed on 13 January 2023).
58. Graves, R.A.; Pearson, S.M.; Turner, M.G. Landscape dynamics of floral resources affect the supply of a biodiversity-dependent cultural ecosystem service. *Landsc. Ecol.* **2017**, *32*, 415–428. [CrossRef]
59. Huang, S.; Zheng, Y.; Cheng, L.L.; Ji, C.Y.; Wang, S.; Dong, J.W. The impact mechanism of urban park health benefit evaluation based on landscape preference. *J. Nanjing For. Univ. (Nat. Sci. Ed.)* **2022**, *46*, 221–228. [CrossRef]
60. Richards, D.R.; Tunçer, B. Using image recognition to automate assessment of cultural ecosystem services from social media photographs. *Ecosyst. Serv.* **2018**, *31*, 318–325. [CrossRef]
61. Yang, Y.C.E.; Passarelli, S.; Lovell, R.J.; Ringler, C. Gendered perspectives of ecosystem services: A systematic review. *Ecosyst. Serv.* **2018**, *31*, 58–67. [CrossRef]
62. Yang, M.W.; Wu, R.W.; Bao, Z.Y.; Yan, H.; Nan, X.E.; Luo, Y.X.; Dai, T.F. Effects of urban park environmental factors on landscape preference based on spatiotemporal distribution characteristics of visitors. *Forests* **2023**, *14*, 1559. [CrossRef]
63. Zhai, X.Z.; Eckart, L. Using social media to explore perceptions of ecosystem services by nature-based solution projects. *Landsc. Archit. Front.* **2020**, *8*, 58–77. [CrossRef]
64. Wang, F.E.; Zheng, S.Y.; Yang, H.R.; Yu, J.; Wang, Y.X.; Wang, Z.M. Regionalization and classification of water eco-environment in Zhejiang Province based on ecosystem service. *Acta Ecologica Sinica* **2022**, *42*, 539–548. [CrossRef]
65. Zhang, H.M.; Cai, L.P.; Billy, B.; Yang, Y.J.; Zhang, J.H. National forest park visitors' connectedness to nature and pro-environmental behavior: The effects of cultural ecosystem service, place and event attachment. *J. Outdoor Recreat. Tour.* **2023**, *42*, 100621. [CrossRef]
66. Oteros-Rozas, E.; Martín-López, B.; González, J.A.; Plieninger, T.; López, C.A.; Montes, C. Socio-cultural valuation of ecosystem services in a transhumance social-ecological network. *Reg. Environ. Chang.* **2014**, *14*, 1269–1289. [CrossRef]
67. Tan, Q.Y.; Gong, C.; Li, S.J.; Ma, N.; Ge, F.C.; Xu, M.X. Impacts of ecological restoration on public perceptions of cultural ecosystem services. *Environ. Sci. Pollut. Res.* **2021**, *28*, 60182–60194. [CrossRef]
68. Calvet-Mir, L.; March, H.; Corbacho-Monné, D.; Gómez-Baggethun, E.; Reyes-García, V. Home garden ecosystem services valuation through a gender lens: A case study in the Catalan Pyrenees. *Sustainability* **2016**, *8*, 718. [CrossRef]
69. Johannes, L.; Andrea, G.; Bonnie, K.; Derek, V.B. The future of crowd-sourced cultural ecosystem services assessments. *Ecosyst. Serv.* **2023**, *60*, 101518. [CrossRef]
70. Cai, K.Y.; Huang, W.W.; Lin, G.S. Bridging landscape preference and landscape design: A study on the preference and optimal combination of landscape elements based on conjoint analysis. *Urban For. Urban Green.* **2022**, *73*, 127615. [CrossRef]
71. Zhou, X.C.; Cen, Q.Y.; Qiu, H.F. Effects of urban waterfront park landscape elements on visual behavior and public preference: Evidence from eye-tracking experiments. *Urban For. Urban Green.* **2023**, *82*, 127889. [CrossRef]
72. Weng, F.F.; Li, X.F.; Xie, Y.Q.; Xu, Z.D.; Ding, F.Z.; Ding, Z.; Zheng, Y.S. Study on multidimensional perception of national forest village landscape based on digital footprint support—Anhui Xidi village as an example. *Forests* **2023**, *14*, 2345. [CrossRef]
73. Wang, R.H.; Zhao, J.W.; Meitner, M.J.; Hu, Y.; Xu, X.L. Characteristics of urban green spaces in relation to aesthetic preference and stress recovery. *Urban For. Urban Green.* **2019**, *41*, 6–13. [CrossRef]
74. Thiele, J.; Albert, C.; Hermes, J.; Haaren, V.C. Assessing and quantifying offered cultural ecosystem services of German river landscapes. *Ecosyst. Serv.* **2020**, *42*, 101080. [CrossRef]
75. Zhang, P.; He, Q.Y.; Chen, Z.X.; Li, X.; Ma, J. An empirical study on the promotion of students' physiological and psychological recovery in green space on campuses in the Post-Epidemic Era. *Int. J. Environ. Res. Public Health* **2023**, *20*, 151. [CrossRef]
76. Li, S.Y.; Li, X.Y.; Liu, F. Aesthetic image of public space based on social media: A case study of Shenzhen. *New Archit.* **2022**, *40*, 31–36. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

*Article*

# How Do Urban Waterfront Landscape Characteristics Influence People's Emotional Benefits? Mediating Effects of Water-Friendly Environmental Preferences

**Chen Yan [1,2], Xiangwu Cai [1], Yuping Wu [3], Xuehong Tang [1], Yuxuan Zhou [1], Qin Yang [1], Fangying Li [1], Siren Lan [1,2] and Li Lin [1,2,*]**

[1] College of Landscape Architecture and Art, Fujian Agriculture and Forestry University, Fuzhou 350108, China; ethanyan@fafu.edu.cn (C.Y.); maybehealth@fafu.edu.cn (X.C.); 52319026006@fafu.edu.cn (X.T.); fafuzyx@fafu.edu.cn (Y.Z.); xp0911@fafu.edu.cn (Q.Y.); lifangying@fafu.edu.cn (F.L.)
[2] National Water Park Research Center, Fuzhou 350108, China
[3] Huadong Engineering (Fujian) Corporation Limited, Fuzhou 350003, China; adacxw@gmail.com
* Correspondence: l.lin@fafu.edu.cn

**Abstract:** Landscapes in urban waterfront spaces are of high societal value as they can meet people's physical, psychological, and social needs for health and well-being, but the relationship between waterfront landscape features and public health benefits has yet to be clarified. From the perspective of blue health, this paper takes blue spaces along the Min River of Fuzhou City as the research object. It constructs the mediation model of "Waterfront landscape characteristic (WLC)→Water-friendly environmental preference (WEP)→Emotional benefit (EB)". The role of WEP in the mechanisms linking WLC and EB in different waterfront spaces was explored through the quantification of indicators, questionnaires, and physiological measurements. The main results showed that (1) the ability of different types of waterfront spaces to arouse positive emotions in the population is characterized by blue-dominated space > co-dominated space > green-dominated space, while the opposite is true in terms of inducing negative emotions; (2) green visibility, blue visibility, naturalness, water-friendliness, and openness are all significantly related to EBs and could affect positive emotions either directly or mediated by WEPs, but openness seems not to affect negative emotions through WEPs; (3) cleanliness affects the population's WEP for the coherence dimension, but has no significant role in improving EBs. This study could expand new ideas for research in habitat health, provide a reference for embodied evidence-based waterfront landscape design, and help promote the construction and development of healthy cities.

**Keywords:** blue health; landscape perception; restorative environment; emotional benefit; urban forests; mediating effect

**Citation:** Yan, C.; Cai, X.; Wu, Y.; Tang, X.; Zhou, Y.; Yang, Q.; Li, F.; Lan, S.; Lin, L. How Do Urban Waterfront Landscape Characteristics Influence People's Emotional Benefits? Mediating Effects of Water-Friendly Environmental Preferences. *Forests* **2024**, *15*, 25. https://doi.org/10.3390/f15010025

Academic Editor: Panteleimon Xofis

Received: 18 November 2023
Revised: 13 December 2023
Accepted: 20 December 2023
Published: 21 December 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The benefits to public health and well-being from blue-green spaces are central to the construction and development of urban habitats [1–3]. Globally, nature deficit disorder puts urban populations in a long-term sub-healthy state [4], while urban forests and urban watersheds provide access to nature [5]. In the meantime, as urban forests are increasingly encroached upon by construction [6], and as populations near large water bodies increase in size, urban blue spaces may become increasingly important sites for recreation. Thus, incorporating evidence on the salutogenic effects of certain exposures to blue spaces into urban planning and development of urban infrastructure could contribute to tackling critical public health challenges [7,8].

With the advancement of waterfront regeneration projects globally over the past 20–30 years, the focus of blue space landscape planning has gradually shifted from economic and ecological benefits to public health services [9,10]. The humanized experience of

sustainable pleasure becomes a long-term endogenous driving force for spatial renewal. A growing body of research confirms that natural environments repair physical and mental health in ways that include attention restoration, stress relief, emotional regulation, and physical activity [2,3,11,12], and waterfront forest environments are of special significance in improving public health and enhancing well-being [1]. However, many studies have considered urban waterfront environments only as part of the urban forest, focusing primarily on the health-promoting effects of vegetation on people [13,14], which may bring about the fact that the health benefits of blue spaces based on the water environment are often overlooked [15].

Moreover, differences in waterfront landscape character could directly affect public health and well-being. On the one hand, McDougall's findings suggest that frequently visiting rivers, canals, and the sea, but not green spaces or lakes, is associated with greater mental well-being [16]. On the other hand, Luo and Zhao found that easy accessibility to waterscape and falling blue space normally implies better mental fatigue recovery for the respondents [17,18]. Nevertheless, most existing studies confirm waterscape's unilateral impact on "public preference" or "psychological recovery", and few people correlate the two, leaving more potential influence pathways unexplored.

Most of the studies on the landscape perception and evaluation of blue space are survey-based, including self-assessment reports, questionnaires, public participation GIS-based surveys, and big data surveys [16,18–20]. Meanwhile, some studies have utilized remotely sensed data and Viewshed tools for spatial statistics and quantification [20,21], while others have used the Bluehealth Environment Assessment Tool (BEAT) and other health element evaluation systems to measure health benefits of waterfront environments [22,23]. The acquisition of data from multiple sources has provided a basis for advancing this research area, but very few of them used objective measures, such as physiological and hormonal measures, to assess the effects of mental health promotion [17].

In addition, the analytical methods for exploring blue health are more diverse, mainly regression analysis, analysis of variance, and path analysis [8–10,24]. However, most empirical studies have explored the correlation or causation between waterfront environments and mental health, and fewer studies have focused on the mediating effects of the population itself in terms of environmental preferences for sensory stimulation, motivation to visit nature, need for physical activity, and need for privacy protection [2]. Notably, it is this mediating effect that adds to the diversity of ways in which blue health is promoted, but it has not yet been clarified by existing research.

Accordingly, the blue open space along the Min River within the city of Fuzhou, China, is used as an example to explore the relationship between the waterfront landscape characteristic, the water-friendly environmental preference, and the emotional benefit. Specifically, based on analyzing the differences in population perceptions of different types of waterfront spaces, the water-friendly environmental preference is used as a mediating variable to explore the influence mechanism of waterfront landscape characteristics on emotional benefits. The research will contribute to the active development of planning and design paradigms oriented towards improving emotional benefits, promoting physical and mental health, and accurately promoting the translation of potential health benefits of urban waterfront spaces.

## 2. Methodology

### *2.1. Conceptual Framework*

As shown in Figure 1, from the perspective of blue health promotion, the hypothesis path of "Waterfront landscape characteristic (WLC)→Water-friendly environmental preference (WEP)→Emotional benefit (EB)" was proposed based on the coupling of the Landscape Perception Theory (LPT) and the Cognitive Appraisal Theory (CAT). The LPT suggests that landscape perception is the process of interaction between a scene's objective features and a person's subjective preferences, which in turn triggers the person's psychological activity or behavior (outcome). Meanwhile, the CAT holds that external stimuli

affect human emotions, and the key to mood changes lies in a person's cognitive activity and appraisal process. The above two theories have been widely recognized and applied in the research fields of environmental psychology, tourism science, and landscape architecture, and their coupled relationship also provides new ideas for the study of the emotional benefits of waterfront spaces [25–27]. Therefore, the hypothesized paths in the conceptual framework could be interpreted as follows. After the aquatic landscape stimulates the senses, a person evaluates the landscape through underlying personal preferences, which in turn generates emotional benefits through psychological changes.

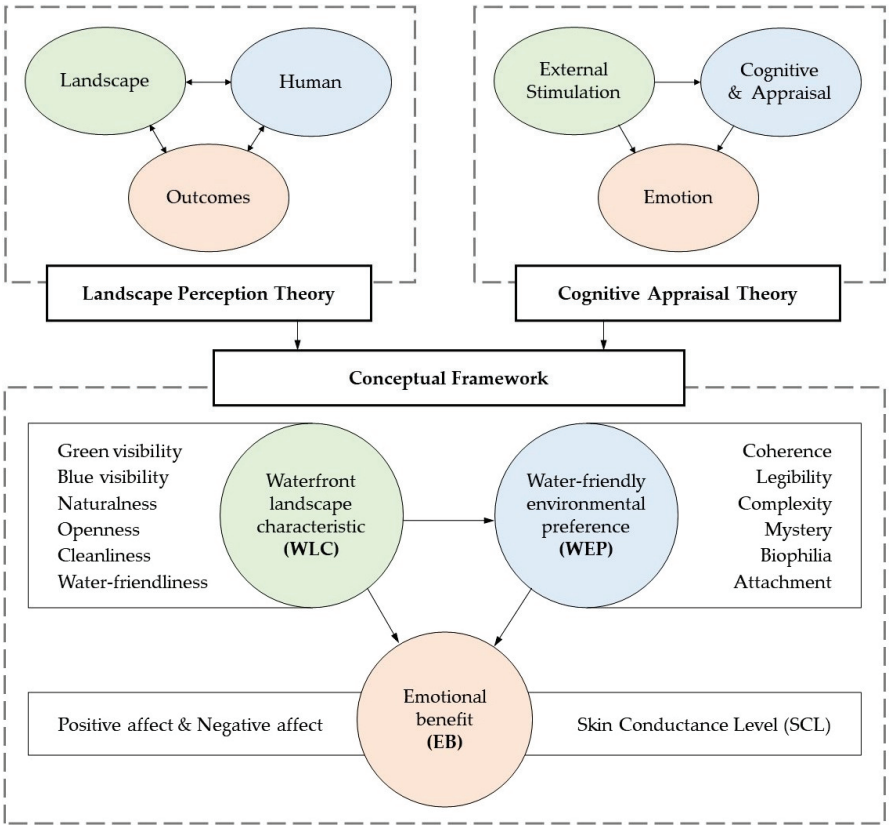



**Figure 1.** Research conceptual framework.

### *2.2. Objects and Sample Sites*

The waterfront spaces of the Min River in Fuzhou, China, were selected for the study. First, Fuzhou is known as one of the most representative provincial capitals in southeastern China, with the central city along the Min River. Thus, the Min River not only drives the development of Fuzhou city, but its waterfront area is also the most crucial ecological landscape belt and recreational space for citizens. Second, since the government implemented the "Min River Landscape Enhancement Project", the waterfront space along the Min River has gradually presented a quality ecological environment and humanistic landscape atmosphere. This project has become one of the most typical cases of renewal in southeast China.

Considering the scale conditions of landscape perception, the waterfront space in this study was defined as an open space that can be used for recreational activities within the reach of human senses and behavior. Since water and vegetation are the most dominant natural elements in the waterfront space, the sample plots along the Min River were classified into three categories based on the dominance of blue and green elements: blue-dominated space (BDS), green-dominated space (GDS), and co-dominated space (CDS). Considering the typicality of the sample plots and the feasibility of the experiment, the study selected a total of 206 waterfront spaces as alternative sample sites along the Min River in the main urban area through field research. Subsequently, a stratified random

sampling method was used to select 14 waterfront spaces (42 in total) in each of the three typologies as official sample sites (Figures 2–4).

**Figure 2.** Photographs of sample sites of blue-dominated space (BDS).

**Figure 3.** Photographs of sample sites of co-dominated space (CDS).

**Figure 4.** Photographs of sample sites of green-dominated space (GDS).

### *2.3. Data Collection*

#### 2.3.1. WLC Indicator Data

The water substrate gives waterfront spaces their unique landscape attributes. Hence, green visibility, blue visibility, openness, cleanliness, naturalness, and water-friendliness are the indicators that best represent the landscape characteristics of the waterfront space [28–31], as shown in Table 1. In this case, the green visibility and blue visibility were calculated from the percentage of the number of grids with the corresponding content after the pixelization of the panoramic photo. The remaining four indicators were derived by scoring each sample site by 50 experts from landscape architecture, urban and rural planning, geography, hydrology, and other related disciplines.

**Table 1.** Interpretation and assessment of WLC indicators.

| Indicator Name | Interpretation | Assessment |
|---|---|---|
| Green visibility | Percentage of plants in vision | Image Semantic Segmentation |
| Blue visibility | Percentage of water in vision | |
| Naturalness | Few artificial landscape interventions | Expert scoring and standardization |
| Water-friendliness | Accessibility to waterfront activities | |
| Openness | Visual permeability and sky exposure | |
| Cleanliness | Tidiness and hygiene of the environment | |

#### 2.3.2. WEP Test Data

The Environmental Preference Scale (EPS) has been used to measure individuals' sensory and use preferences for the environment, and it contains four dimensions: coherence, legibility, complexity, and mystery [32]. Since humans have innate biophilic traits and exhibit solid water environment attachment [33,34], the study supplemented the EPS with biophilia and attachment dimensions, expanding it into the Water-friendly Environmental

Preferences Scale (WEPS), as shown in Table 2. Moreover, all questions in the WEPS were contextualized around urban waterfront spaces and scored using the 5-point Likert Scale to better measure individuals' subjective and behavioral preferences in waterfront spaces.

**Table 2.** Dimensions and contents of the WEPS.

| Dimension | Interpretation | Contents (Items) |
|---|---|---|
| Coherence | Extent to which scene "hangs together" | The style of the waterfront scene is very consistent.<br>The waterfront landscape elements hang together well.<br>It is easy to organize and structure the waterfront landscape. |
| Legibility | Extent to which scene is easily recognized | It is easy to find my way around this waterfront space.<br>The waterscape helps me figure out where I am.<br>The position of different landscape elements is very clear. |
| Complexity | Extent to which scene contains many elements | This scene contains a lot of elements of different kinds.<br>This waterfront scenery is dazzling.<br>This waterfront landscape looks changeful. |
| Mystery | Extent to which scene promises further information | This waterfront view looks secluded and profound.<br>This waterscape could arouse my interest in further exploration.<br>The setting seems to invite me to enter more deeply into it. |
| Biophilia | Extent to which scene is close to original nature | This waterfront landscape has a sense of vitality.<br>The natural and artificial landscapes here are harmonious.<br>This waterfront space allows me to get very close to nature. |
| Attachment | Extent to which scene creates a sense of dependence | I would like to revisit this waterfront space.<br>Compared to other waterfront spaces, this is more suitable for me.<br>Overall, I like this waterfront space. |

#### 2.3.3. EB Test Data

As shown in Table 3, the Positive and Negative Affect Scale (PANAS) is used to measure the emotional well-being of the population [35], and people can self-rate each emotion on the 5-point Likert Scale. Since changes in skin conductance level (SCL) are most responsive to sympathetic nerve activity and emotional arousal levels, they could be used to aid in validating changes in the emotional benefits of individuals in different types of waterfront spaces. Therefore, the Ergo LAB physiological recorder developed by Beijing Kingfar Science and Technology Co., Ltd (Beijing, China). was used to collect the SCL of the subjects in real time. When SCL values are elevated, it indicates that the individual is in a state of anxiety or alertness; conversely, it indicates a state of pleasure or relaxation [36].

**Table 3.** Dimensions and descriptors of PANAS.

| Dimension | Descriptors |
|---|---|
| Positive affect (PA) | Enthusiastic; Interested; Active; Strong; Inspired;<br>Alert; Determined; Excited; Proud; Attentive |
| Negative affect (NA) | Scared; Afraid; Upset; Distressed; Jittery;<br>Nervous; Ashamed; Guilty; Irritable; Hostile |

### *2.4. Experimental Process*

Numerous studies in environmental psychology and sociology have concluded that the assessment results of student population samples are highly consistent with those of the general mass population [37,38]. Accordingly, 150 university students (66 males and 84 females) were randomly recruited to participate in the study, and each subject maintained a healthy physical condition and normal emotional state throughout the experiment. It should be stated that all subjects participated in this experiment voluntarily and agreed to use the questionnaire data and physiological data for scientific research and academic publication. This experiment was conducted in July this year at the Landscape Perception

Laboratory of Fujian Agriculture and Forestry University, and the panoramic photographs of each sample plot were previously projected on a large screen in the audio-visual room. The exact procedure of the experiment is as follows:

1. Prior to the start of the experiment, participants were informed of the purpose and content of the experiment and could discontinue the ongoing test at any time if they felt any discomfort during the experiment.
2. At the beginning of the experiment, the SCL baseline values were recorded while the subjects were in an emotionally calm state.
3. Subjects entered the audio-visual room of the sample site for about 5 min to experience the simulated scene, during which time SCL data were in a continuous recording state.
4. After that, subjects filled out the WEPS and the PANAS, and the experiment ended.

### 2.5. Data Analysis

First, in the data processing stage, outlier tests and dataset corrections were performed on the physiological data using the data analysis module built into the Ergo LAB wireless sensor system. Moreover, reliability and validity tests and normal distribution tests were performed on the data measured by the scales, and data that did not satisfy normality were transformed.

Second, in the stage of variability and correlation analysis, descriptive statistical analysis and analysis of variance (ANOVA) were used to present the variability of landscape perceptions in different types of waterfront spaces, while Pearson and Spearman correlation analyses were used to explore the correlations among WLC, WEP, and EB, as well as among the dimensions. The results of the above analysis are mainly presented in Sections 3.1 and 3.2.

Third, in the stage of hypothetical pathways and conceptual model validation, mediation regression analyses were used to investigate the mediating effect of WEP between WLC and EB, with residual tests. Categorical variables were converted to pseudo-variables for computation in the treatment process [39,40]. The results of the mediating analysis are presented in Section 3.3.

## 3. Results

The potential association between WLC, WEP, and EB, as well as the path of influence between their dimensions, is the key to this study. Therefore, synthesizing the above research methodology and data analysis process, the findings are analyzed and presented in terms of relationship between WLC and WEP, relationship between WLC and EB, and mediating effect of WEP between WLC and EB.

### 3.1. Relationship between WLC and WEP

The WEP of the population for three types of waterfront spaces showed significant differences in all dimensions ($p < 0.001$), and the degree of preference, from high to low, was as follows: CDS > BDS > GDS (Table 4). In addition, most WLCs were strongly correlated with the WEP, as shown in Table 5. Specifically, green visibility, blue visibility, naturalness, and water-friendliness could enhance people's WEP; conversely, openness exhibits a weakening effect on coherence, complexity, mystery, and biophilia, in addition to boosting legibility, and cleanliness is correlated only with coherence.

**Table 4.** WEP evaluation (mean ± SE) and difference of 3 types of waterfront spaces.

| | Coherence | Legibility | Complexity | Mystery | Biophilia | Attachment |
|---|---|---|---|---|---|---|
| Blue-dominated space | 3.60 ± 0.81 | 4.03 ± 0.61 | 3.07 ± 0.81 | 2.92 ± 1.01 | 3.32 ± 0.89 | 3.37 ± 0.81 |
| Green-dominated space | 3.44 ± 0.76 | 3.63 ± 0.81 | 2.64 ± 0.89 | 2.34 ± 0.85 | 2.27 ± 0.75 | 2.76 ± 0.86 |
| Co-dominated space | 4.11 ± 0.73 | 4.31 ± 0.61 | 3.37 ± 0.85 | 3.75 ± 0.94 | 4.37 ± 0.65 | 4.03 ± 0.68 |
| F | 9.84 *** | 11.90 *** | 8.31 *** | 25.51 *** | 80.86 *** | 29.95 *** |

Note: *** $p < 0.001$.

**Table 5.** Correlation between WLC and WEP.

| | WLC Indicators | Coherence | Legibility | Complexity | Mystery | Biophilia | Attachment |
|---|---|---|---|---|---|---|---|
| Pearson | Green visibility | 0.36 ** | 0.36 ** | 0.28 ** | 0.53 ** | 0.67 ** | 0.53 ** |
| | Blue visibility | 0.31 ** | 0.36 ** | 0.25 ** | 0.44 ** | 0.62 ** | 0.47 ** |
| Spearman | Naturalness | 0.34 ** | 0.36 ** | 0.32 ** | 0.50 ** | 0.73 ** | 0.53 ** |
| | Water-friendliness | 0.36 ** | 0.38 ** | 0.12 | 0.49 ** | 0.66 ** | 0.52 ** |
| | Openness | −0.24 ** | 0.32 ** | −0.18 * | −0.34 ** | −0.36 ** | −0.12 |
| | Cleanliness | 0.23 ** | −0.15 | −0.02 | 0.10 | 0.11 | 0.09 |

Note: * $p < 0.05$, ** $p < 0.01$.

### *3.2. Relationship between WLC and EB*

The ability of three types of waterfront spaces to evoke positive emotions was shown to be CDS > BDS > GDS, and the opposite was found in terms of inducing negative emotions (Table 6). Meanwhile, as shown in Figure 5, the mean value of the decrease in skin conductance level of the population showed that CDS (0.57 ± 0.19) > BDS (0.45 ± 0.21) > GDS (0.28 ± 0.18), which was in line with the trend of the evaluation results of the PANAS. Moreover, WLCs were closely related to an individual's EB (Table 7). To be specific, green visibility, blue visibility, naturalness, and water-friendliness were all significantly positively correlated with positive emotions and significantly negatively correlated with negative emotions. In contrast, the opposite was true for openness, and cleanliness was not seen to be correlated with emotional benefits.

**Table 6.** EB Evaluation (mean ± SE) and difference of 3 types of waterfront spaces.

| | Positive Affect | Negative Affect |
|---|---|---|
| Blue-dominated space | 3.00 ± 0.73 | 1.43 ± 0.51 |
| Green-dominated space | 2.89 ± 0.95 | 1.56 ± 0.77 |
| Co-dominated space | 3.68 ± 0.58 | 1.12 ± 0.28 |
| F | 10.71 *** | 5.29 ** |

Note: ** $p < 0.01$, *** $p < 0.001$.

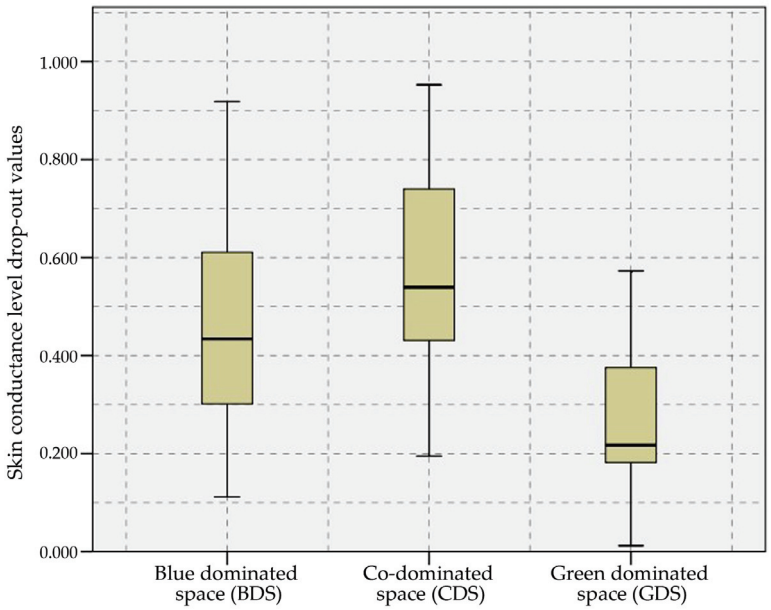



**Figure 5.** SCL drop-out values in 3 types of waterfront spaces.

**Table 7.** Correlation between WLC and EB.

| | WLC Indicators | Positive Affect | Negative Affect |
|---|---|---|---|
| Pearson | Green visibility | 0.35 ** | −0.27 ** |
| | Blue visibility | 0.28 ** | −0.28 ** |
| Spearman | Naturalness | 0.33 ** | −0.26 ** |
| | Water-friendliness | 0.32 ** | −0.28 ** |
| | Openness | −0.18 * | 0.19 * |
| | Cleanliness | 0.08 | 0.02 |

Note: * $p < 0.05$, ** $p < 0.01$.

### 3.3. Mediating Effect of WEP between WLC and EB

First, as shown in Table 8, all dimensions of WEP were significantly correlated with both PA and NA. Second, in the mediation model of "WLC→WEP→EB", WEP, besides cleanliness, was shown to mediate between WLCs and EB (Table 9). The results showed that green visibility, blue visibility, naturalness, and water-friendliness all influenced PA and NA through WEP, while WEP could only play a mediating role when openness affected PA, and the mediating effect on NA was not significant (Figure 6).

**Table 8.** Pearson's correlation between WEP and EB.

| | Positive Affect | Negative Affect |
|---|---|---|
| Coherence | 0.51 ** | −0.27 ** |
| Legibility | 0.48 ** | −0.29 ** |
| Complexity | 0.57 ** | −0.30 ** |
| Mystery | 0.70 ** | −0.39 ** |
| Biophilia | 0.70 ** | −0.50 ** |
| Attachment | 0.78 ** | −0.51 ** |

Note: ** $p < 0.01$.

**Table 9.** Regression analysis of the mediating model of "WLC→WEP→EB".

| | X→M | | X→$Y_{PA}$ | | X→M→$Y_{PA}$ | | X→$Y_{NA}$ | | X→M→$Y_{NA}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | β | t | β | t | β | t | β | t | β | t |
| Green visibility | 0.02 | 7.62 *** | 0.01 | 4.60 *** | −0.00 | −1.45 | −0.01 | −3.38 *** | 0.00 | 0.06 |
| | | | | | 0.72 | 13.83 *** | | | −0.31 | −6.16 *** |
| $R^2$ | 0.28 | | 0.12 | | 0.62 | | 0.07 | | 0.26 | |
| F | 58.02 *** | | 21.12 *** | | 119.69 *** | | 11.44 *** | | 26.12 *** | |
| Blue visibility | 0.11 | 6.40 | 0.06 | 3.60 *** | −0.02 | −1.81 | −0.39 | −3.53 *** | −0.01 | 0.65 |
| | | | | | 0.73 | 14.53*** | | | −0.29 | −6.10*** |
| $R^2$ | 0.22 | | 0.08 | | 0.62 | | 0.08 | | 0.26 | |
| F | 40.99 *** | | 12.98 *** | | 121.20 *** | | 12.49 *** | | 26.40 *** | |
| Naturalness | 0.64 | 7.76 *** | 0.34 | 4.26 *** | −0.13 | −2.14 ** | −0.19 | −3.28 ** | 0.02 | 0.25 |
| | | | | | 0.74 | 14.24 | | | −0.32 | −6.23 *** |
| $R^2$ | 0.29 | | 0.11 | | 0.62 | | 0.07 | | 0.26 | |
| F | 60.23 *** | | 18.15 *** | | 122.89 *** | | 10.76 ** | | 26.16 *** | |
| Water-friendliness | 0.76 | 7.51 *** | 0.39 | 3.99 *** | −0.17 | −2.33 ** | −0.22 | −3.11 ** | 0.03 | 0.36 |
| | | | | | 0.75 | 14.47*** | | | −0.32 | −6.34 *** |
| $R^2$ | 0.28 | | 0.10 | | 0.63 | | 0.06 | | 0.26 | |
| F | 56.36 *** | | 15.95 *** | | 123.98 *** | | 9.65 ** | | 26.20 *** | |
| Openness | −0.25 | −4.13 *** | −0.12 | −2.15 *** | 0.06 | 1.62 | 0.13 | 1.54 | | |
| | | | | | 0.71 | 15.13 *** | | | | |
| $R^2$ | 0.10 | | 0.03 | | 0.62 | | | | | |
| F | 17.03 ** | | 4.62 *** | | 120.35 *** | | | | | |
| Cleanliness | | | −0.07 | −0.80 | | | −0.05 | −0.60 | | |
| $R^2$ | | | | | | | | | | |
| F | | | | | | | | | | |

Note: ** $p < 0.01$, *** $p < 0.001$.

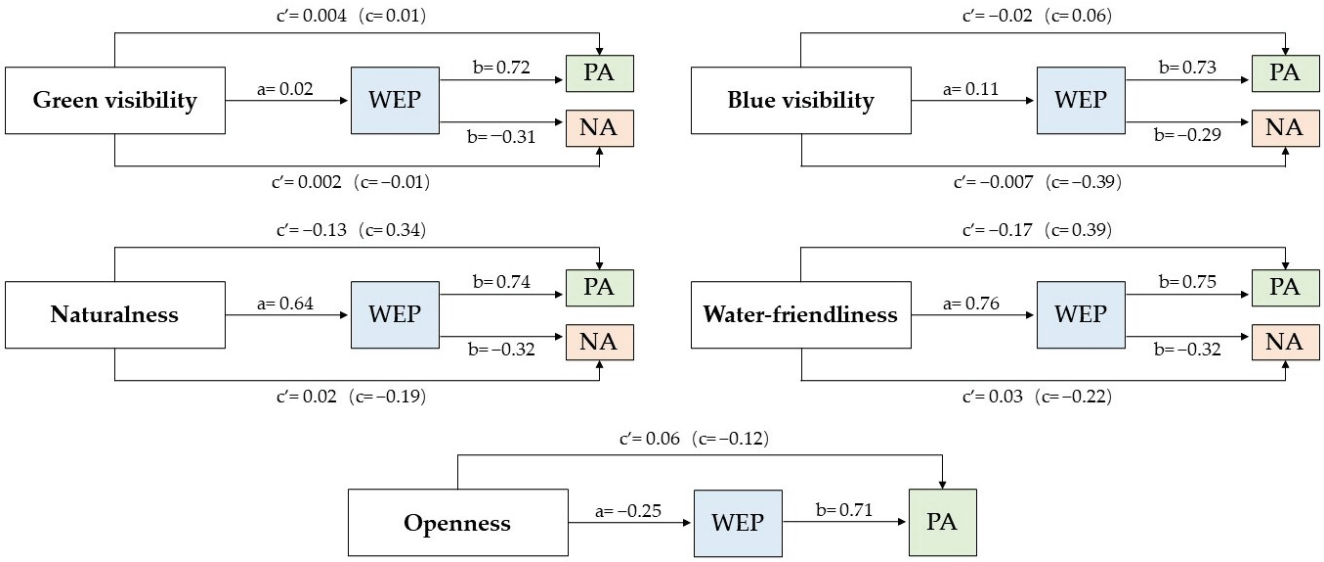



**Figure 6.** Mediating models of "WLC→WEP→EB".

## 4. Discussion

### *4.1. Differences of EBs in 3 Types of Waterfront Spaces*

The results suggested that the population showed significantly higher water environmental preferences and elevated moods in both BDS and CDS than in GDS (Tables 4 and 6, and Figure 5). Because of the high degree of exposure to water and the natural hydrophilic conditions of BDS and CDS, which could easily trigger an individual's innate hydrophilicity, the population may be able to promote physical and mental health restoration due to the enhancement of aquaphilic perception [41]. On the contrary, when one is in a GDS, one's visual sensitivity to the waterscape is reduced due to the high visibility of the vegetated landscape, which in turn diminishes the emotional benefits produced by the water. This result also corroborates the findings that water features often produce more significant psychological restorative effects than other landscape elements [42,43].

Furthermore, the study found that the emotional benefits of CDS were slightly higher than those of BDS, given similar water-friendly conditions. Similarly, a study of preference and emotional feedback on water exposure showed that scenes containing only water were rated less positively than ones with two-thirds water and one-third green [24].

First, it has to do with the physiologically evolved human need for survival and safety. Biologists believe that humans are naturally attracted to water-rich habitats, but that their physiological adaptations to terrestrial environments dictate a degree of existential threat to aquatic environments [33,44]. Therefore, the best environment to meet the physical and mental needs of human beings is a waterfront area between land and water, but at a safe distance from the water [45]. In further research, Pitt also revealed the negative effects produced by bodies of water; when a person observes the surface of the water immediately adjacent to the riverbank, the lower visibility of the depth of the water can lead to a heightened sense of nervousness and vigilance by making the person perceive unknown risks, and even perceive threats from other species [46].

Second, the landscape elements of CDSs, which consist of both urban forests and waters, are more varied and have richer plant landscapes than BDSs, which rely solely on water. Relevant studies have also found that the coexistence of multiple landscape types can increase the complexity and mystery of the environment, and these two characteristics can better stimulate human vision, inspire the desire to explore, and awaken positive emotions [47,48]. At the same time, the emotional benefits generated by the waterscape are thought to be able to superimpose with other landscapes, such as plant communities, and another experiment confirmed that crowds prefer waterfront spaces with rich and varied vegetation [49].

### 4.2. Effects of Different WLCs on EBs

The correlation between WLCs and EBs showed that green visibility, blue visibility, naturalness, and water-friendliness all enhanced positive affect and diminished negative affect (Table 7). All of the above indicators reflect the keynote role played by planted landscapes and water features in the promotion of emotional benefits [24,49–51]. First of all, a waterfront space close to the natural state not only improves the microclimate and enhances physiological comfort, but also enriches the sensory experience and promotes psychological pleasure. Secondly, leisure activities near water and physical interactions with water are effective in increasing the arousal of positive affect and guiding emotional relief. Lastly, the intimate scale space delineated by vegetation and water encourages people to open up and creates more opportunities for socialization, which helps to enhance the individual's sense of self-identity. As Gidlow's study found, walking in green and blue environments could improve people's resilience and perception compared to walking in urban environments [52]. By no coincidence, Daniel identified an association between increased views of blue space and decreased psychological distress [41].

Interestingly, it was found that waterfront spaces with a high degree of openness were not only detrimental to the promotion of positive emotions, but also had the potential to trigger negative emotions. While some studies have shown that high openness of the shoreline could stimulate visual sensations, and enhance the space's vitality, which provides a reason to linger, there is no direct evidence of its effect on emotional benefits [53–55]. However, there are still related studies that showed similar results. Although the open waterfront space could give people a bright visual experience and bring them a short-lived feeling of surprise, after a period of time, this transient emotion would gradually be replaced by negative emotions such as boredom and agitation [56,57]. As some findings suggest, overly open environments tend to put people in a disturbed state of being watched and monitored by others all the time, which might lead to nervousness and restlessness [58,59].

Conversely, some studies on the openness of street space have found that open sightlines and sky visibility contribute to psychological stress relief [60], suggesting that the same landscape characteristic may be perceived more differently in environments with different attributes. Specifically, the street space itself has a more obvious sense of oppression; the openness can easily and quickly awaken people's positive emotions under the strong contrast perception. While the waterfront space has a high degree of openness on the whole, excessive openness can easily induce negative emotions due to the reduction in the sense of security and intimacy.

### 4.3. Paths of WLCs to EBs under the Mediating Effect of the WEP

Based on the "WLC→WEP→EB" mediation modeling, it was found that green visibility, blue visibility, naturalness, and water-friendliness all significantly enhanced people's WEP (Table 5) and were able to influence emotional benefits through the mediation of WEP (Figure 6). Similar findings showed that water-friendly landscape amenities could enhance residents' environmental preferences, which in turn influence well-being through its mediating effect [53]. The above results suggest that the demand for waterfront space is better met by an urban landscape that resembles pristine nature, rich biodiversity, and convenient access to water. By enhancing an individual's preference for water environments, these WLCs not only provide spiritual solace, inspiration, and enlightenment, but also reduce the mental rumination of past painful experiences [61], whereas waterfront landscapes with too many artificial traces of construction, lack of vitality, and poor waterplay experience do not meet the environmental preferences of the population and are more likely to trigger negative emotions that are not conducive to physical and mental health [10].

In addition, cleanliness was found to be related only to the coherence dimension of the WEP (Table 5), but not only was it not related to EBs (Table 7), but it also did not have an effect on EBs through the mediation of the WEP (Table 9). Another related experiment yielded very different results, with cluttered environments negatively affecting restorative perceptions, while environments that are relaxing are usually tidy [49,62]. The reasons for

such differences may be as follows. First, there are endogenous differences in the public's tolerance of clutter or understanding of tidiness. Second, very different experimental materials such as panoramic photographs, virtual scenes, or real environments can lead to different intensities of perception of the characteristic of cleanliness, thus yielding experimental results that are not entirely consistent.

It is worth noting that, contrary to most WLCs, openness could negatively affect positive emotions through the mediation of the WEP, and related studies have drawn similar conclusions to those above from perspectives such as ecological perception and cultural identity [63,64]. This path of influence suggests that although openness of the site can generate surprise and excitement for a short period of time, it tends to trigger psychological distance due to its overall lack of closeness and shelter. Thus, openness produces strong negative effects on the mystery and biophilia dimensions of the WEP and attenuates positive emotions through its mediating effect.

Surprisingly, there was a significant positive correlation between openness and negative affect, but there was no mediating effect of the WEP in the path of the former on the latter. This result suggests that open spaces, while prone to triggering negative emotions, are not necessarily caused by the WEP, which may be triggered by other psychological states or behaviors of the population. For example, if the landscape level is too homogeneous, it is easy to cause aesthetic fatigue of the public, while in a space with a high degree of freedom of movement, the landscape is believed to guide the mood fluctuation through the clustering and modulation of behavioral activities [56,65]. Therefore, how the openness of waterfront spaces affects the emotional well-being of individuals in multiple ways remains to be further explored.

### *4.4. Landscape Optimization Strategies for Urban Waterfront Spaces*

Synthesizing the above findings, the study aims to enhance individuals' water-friendly environmental preferences and propose landscape optimization strategies for urban waterfront spaces that contribute to emotional benefits [10,35,49,64].

1. On the premise of meeting the needs of public activities, the greening area and water area, including three-dimensional greening and three-dimensional water features, could be appropriately increased, and rendered close to the original natural state.
2. It is desirable to reduce the hardened state of the barge area and plant aquatic plants, but the percentage of aquatic plants in the water should be controlled to avoid reducing the blue visibility due to excessive reduction in the watershed area.
3. A certain richness of landscape elements is required, but care should be taken to order the landscape and avoid over-design.
4. Based on the safety protection design, water-friendly platforms or walkways could be set up close to the water surface to shorten the distance between people and water; Water sports and recreational facilities could also be added to meet the needs of different people's water activities.
5. In open spaces with larger scales, spatial boundaries and traffic guidance should be strengthened and secondary semi-enclosed spaces should be delineated using plant groups and other landscape facilities to enhance the sense of environmental shelter and spatial domain for the crowd.
6. Water should be allowed to circulate and flow, the self-purification ability of water should be enhanced, the overall environmental hygiene and cleanliness of the waterfront space should be maintained, the daily management and maintenance of public facilities should be strengthened, and a public participation and monitoring mechanism should be established.

## 5. Conclusions

Taking three types of waterfront spaces along the Min River in Fuzhou, China, as an example, this study explored the differences in the EB of populations in different types of spaces, and explored the associations between different WLCs and changes in individual

EBs. Furthermore, the study attempted to analyze the mediating effect of WEPs in the process of WLCs influencing EBs, and then revealed the multiple paths of influence of WLCs on individual EBs. The main findings of the study are as follows.

1. Urban waterfront spaces could effectively improve the EBs of the crowd; CDSs were the most consistent with the population's WEPs and had the strongest effect on the promotion of positive emotions and the alleviation of negative emotions, followed by BDSs, while GDSs had the weakest effect.
2. Green visibility, blue visibility, naturalness, and water-friendliness tend to influence people's EBs both directly and through the mediating effect of WEPs; in other words, lush and orderly planted landscapes, permeable water visibility, moderate signs of man-made structures, easy access to water, and a good water experience help improve the emotional quality of the population.
3. Openness could directly affect or be mediated by WEPs to influence positive emotions, and overly open waterfront spaces are not conducive to improving the quality of emotions. Although openness has been shown to influence negative emotions, there is no evidence that the former can be mediated by WEPs, and the pathways of influence need to be further explored.
4. Cleanliness affects the coherence dimension of the WEP, but has no significant effect on the other dimensions, nor does it play a significant role in improving EBs.
5. Under the perspective of blue health, the landscape of urban waterfront spaces should be gradually optimized by enhancing the blue-green visibility, naturalness, and water-friendliness, controlling the degree of openness, and maintaining the degree of cleanliness.

In summary, the study took urban waterfront space as the object and conducted exploratory research based on the coupling of the Landscape Perception Theory and the Cognitive Appraisal Theory, providing a new idea for the correlation research between the objective characteristics of the environment and the subjective perception of individuals. However, this study still has some limitations. In the first place, since the focus has been on visual sensory stimulation in landscape perception, while auditory, olfactory, and tactile senses have not been explored, it is expected that the pathways of the influence of WLCs on EBs under different dimensions of senses will be refined in further research and practical work. In addition, due to the differences in the natural and social environments of different regions, another important in-depth study in further steps will be to distinguish the characteristics of the samples across time and space to expand the scope of application and practical significance of the mediation model.

**Author Contributions:** Conceptualization, C.Y. and Y.W.; methodology, C.Y.; software, X.C., C.Y. and X.T.; validation, Y.Z. and Q.Y.; formal analysis, X.C. and Y.W.; investigation, Y.W., X.C., X.T., Y.Z. and Q.Y.; resources, C.Y., F.L. and S.L.; data curation, X.T., Y.Z. and X.C.; writing—original draft preparation, C.Y., X.C. and Y.W.; writing—review and editing, C.Y. and L.L.; visualization, X.C.; supervision, F.L. and S.L.; project administration, L.L.; funding acquisition, C.Y. and L.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Fujian Social Science Planning Project, grant number: FJ2021C038; Education and Research Project for Middle and Young Teachers in Fujian Province, grant number: JAT220058; Fujian First-class Undergraduate Program, grant number: 111902108.

**Data Availability Statement:** The data used to support the findings of this study are available from the corresponding author upon request.

**Acknowledgments:** First, the authors would like to thank all members of the livable water environment research team for their support in this study, including Wei Zhou and Jintao Chen, for their active assistance during the experiment. Secondly, we are grateful to Jianwen Dong, Minhua Wang, and Weicong Fu for their valuable suggestions for this paper. Also, special thanks are given to Jialu Chen, Nan Yang, Xunan Li, Yanping Dai, Xinru Lu, Haiyang Yu, and Jingyan Wu for their participation in data collection, as well as Weijun Ji, Bingbing Cheng, and Xiaofeng Wu for their daily

support and care. Finally, we also thank all the people who participated in the questionnaire survey and experiment.

**Conflicts of Interest:** Author Yuping Wu was employed by the company Huadong Engineering (Fujian) Corporation Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## References


1. Poulsen, M.N.; Nordberg, C.M.; Fiedler, A.; De Walle, J.; Mercer, D.; Schwartz, B.S. Factors associated with visiting freshwater blue space: The role of restoration and relations with mental health and well-being. *Landsc. Urban Plan.* **2022**, *217*, 104282. [CrossRef]
2. Yen, H.-Y.; Chiu, H.-L.; Huang, H.-Y. Green and blue physical activity for quality of life: A systematic review and meta-analysis of randomized control trials. *Landsc. Urban Plan.* **2021**, *212*, 104093. [CrossRef]
3. Reeves, J.P.; John, C.H.D.; Wood, K.A.; Maund, P.R. A qualitative analysis of UK wetland visitor centres as a health resource. *Int. J. Environ. Res. Public Health* **2021**, *18*, 8629. [CrossRef] [PubMed]
4. Birch, J.; Rishbeth, C.; Payne, S.R. Nature doesn't judge you—How urban nature supports young people's mental health and wellbeing in a diverse UK city. *Health Place* **2020**, *62*, 102296. [CrossRef] [PubMed]
5. Escobedo, F.J.; Giannico, V.; Jim, C.Y.; Sanesi, G.; Lafortezza, R. Urban forests, ecosystem services, green infrastructure and nature-based solutions: Nexus or evolving metaphors. *Urban For. Urban Green.* **2019**, *37*, 3–12. [CrossRef]
6. Guo, L.-H.; Cheng, S.; Liu, J.; Wang, Y.-Y.; Cai, Y.-S.; Hong, X.-C. Does social perception data express the spatio-temporal pattern of perceived urban noise? A case study based on 3,137 noise complaints in Fuzhou, China. *Appl. Acoust.* **2022**, *201*, 109129. [CrossRef]
7. Thompson, C.W. Activity, exercise and the planning and design of outdoor spaces. *J. Environ. Psychol.* **2013**, *34*, 79–96. [CrossRef]
8. Li, X.; Wang, X.; Jiang, X.; Han, J.; Wang, Z.; Wu, D.; Lin, Q.; Li, L.; Zhang, S.; Dong, Y. Prediction of riverside greenway landscape aesthetic quality of urban canalized rivers using environmental modeling. *J. Clean. Prod.* **2022**, *367*, 133066. [CrossRef]
9. Smith, N.; Georgiou, M.; King, A.C.; Tieges, Z.; Webb, S.; Chastin, S. Urban blue spaces and human health: A systematic review and meta-analysis of quantitative studies. *Cities* **2021**, *119*, 103413. [CrossRef]
10. Li, J.; Huang, Z.; Zheng, D.; Zhao, Y.; Huang, P.; Huang, S.; Fang, W.; Fu, W.; Zhu, Z. Effect of landscape elements on public psychology in urban park waterfront green space: A quantitative study by semantic segmentation. *Forests* **2023**, *14*, 244. [CrossRef]
11. Elliott, L.R.; Pasanen, T.; White, M.P.; Wheeler, B.W.; Grellier, J.; Cirach, M.; Bratman, G.N.; van den Bosch, M.; Roiko, A.; Ojala, A.; et al. Nature contact and general health: Testing multiple serial mediation pathways with data from adults in 18 countries. *Environ. Int.* **2023**, *178*, 108077. [CrossRef] [PubMed]
12. White, M.P.; Alcock, I.; Wheeler, B.W.; Depledge, M.H. Would you be happier living in a greener urban area? A fixed-effects analysis of panel data. *Psychol. Sci.* **2013**, *24*, 920–928. [CrossRef] [PubMed]
13. Li, S.-Y.; Chen, Z.; Guo, L.-H.; Hu, F.; Huang, Y.-J.; Wu, D.-C.; Wu, Z.; Hong, X.-C. How do spatial forms influence psychophysical drivers in a campus city community life circle? *Sustainability* **2023**, *15*, 10014. [CrossRef]
14. Stigsdotter, U.K.; Corazon, S.S.; Sidenius, U.; Refshauge, A.D.; Grahn, P. Forest design for mental health promotion-using perceived sensory dimensions to elicit restorative responses. *Landsc. Urban Plan.* **2017**, *160*, 1–15. [CrossRef]
15. White, M.P.; Elliott, L.R.; Gascon, M.; Roberts, B.; Fleming, L.E. Blue space, health and well-being: A narrative overview and synthesis of potential benefits. *Environ. Res.* **2020**, *191*, 110169. [CrossRef] [PubMed]
16. McDougall, C.W.; Hanley, N.; Quilliam, R.S.; Oliver, D.M. Blue space exposure, health and well-being: Does freshwater type matter? *Landsc. Urban Plan.* **2022**, *224*, 104446. [CrossRef]
17. Luo, L.; Yu, P.; Jiang, B. Differentiating mental health promotion effects of various bluespaces: An electroencephalography study. *J. Environ. Psychol.* **2023**, *88*, 102010. [CrossRef]
18. Zhao, J.; Xu, W.; Ye, L. Effects of auditory-visual combinations on perceived restorative potential of urban green space. *Appl. Acoust.* **2018**, *141*, 169–177. [CrossRef]
19. Kajosaari, A.; Pasanen, T.P. Restorative benefits of everyday green exercise: A spatial approach. *Landsc. Urban Plan.* **2021**, *206*, 103978. [CrossRef]
20. Hong, X.-C.; Cheng, S.; Liu, J.; Guo, L.-H.; Dang, E.; Wang, J.-B.; Cheng, Y. How should soundscape optimization from perceived soundscape elements in urban forests by the riverside be performed? *Land* **2023**, *12*, 1929. [CrossRef]
21. Dempsey, S.; Devine, M.T.; Gillespie, T.; Lyons, S.; Nolan, A. Coastal blue space and depression in older adults. *Health Place* **2018**, *54*, 110–117. [CrossRef] [PubMed]
22. Vert, C.; Gascon, M.; Ranzani, O.; Marquez, S.; Triguero-Mas, M.; Carrasco-Turigas, G.; Arjona, L.; Koch, S.; Llopis, M.; Donaire-Gonzalez, D.; et al. Physical and mental health effects of repeated short walks in a blue space environment: A randomised crossover study. *Environ. Res.* **2020**, *188*, 109812. [CrossRef] [PubMed]
23. Mishra, H.S.; Bell, S.; Vassiljev, P.; Kuhlmann, F.; Niin, G.; Grellier, J. The development of a tool for assessing the environmental qualities of urban blue spaces. *Urban For. Urban Green.* **2020**, *49*, 126575. [CrossRef]
24. White, M.; Smith, A.; Humphryes, K.; Pahl, S.; Snelling, D.; Depledge, M. Blue space the importance of water for preference, affect, and restorativeness ratings of natural and built scenes. *J. Environ. Psychol.* **2010**, *30*, 482–493. [CrossRef]

25. Yang, G.; Yu, Z.; Zhang, J.; Kristensen, L.S. From preference to landscape sustainability: A bibliometric review of landscape preference research from 1968 to 2019. *Ecosyst. Health Sustain.* **2021**, *7*, 1948355. [CrossRef]
26. Li, P.; Xiao, X.; Jordan, E. Tourists' visual attention and stress intensity in nature-based tourism destinations: An eye-tracking study during the covid-19 pandemic. *J. Travel Res.* **2023**, *62*, 1667–1684. [CrossRef]
27. Welsch, H.; Binder, M.; Blankenberg, A.-K. Green behavior, green self-image, and subjective well-being: Separating affective and cognitive relationships. *Ecol. Econ.* **2021**, *179*, 106854. [CrossRef]
28. Chiang, Y.-C.; Li, D.; Jane, H.-A. Wild or tended nature? The effects of landscape location and vegetation density on physiological and psychological responses. *Landsc. Urban Plan.* **2017**, *167*, 72–83. [CrossRef]
29. Foley, R.; Kistemann, T. Blue space geographies: Enabling health in place. *Health Place* **2015**, *35*, 157–165. [CrossRef]
30. Hu, X.; Zou, X.; Fan, H. Analysis of landscape influencing factors of urban waterfront greenways based on the scenic beauty estimation method, taking Tongjian lake in Hangzhou as an example. *Front. Earth Sci.* **2023**, *11*, 1211775. [CrossRef]
31. Sun, D.; Li, Q.; Gao, W.; Huang, G.; Tang, N.; Lyu, M.; Yu, Y. On the relation between visual quality and landscape characteristics: A case study application to the waterfront linear parks in Shenyang, China. *Environ. Res. Commun.* **2021**, *3*, 115013. [CrossRef]
32. van der Jagt, A.P.N.; Craig, T.; Anable, J.; Brewer, M.J.; Pearson, D.G. Unearthing the picturesque: The validity of the preference matrix as a measure of landscape aesthetics. *Landsc. Urban Plan.* **2014**, *124*, 1–13. [CrossRef]
33. Edward, O.W. *Biophilia*; Harvard University Press: Cambridge, UK, 1984.
34. Lewicka, M. Place attachment: How far have we come in the last 40 years? *J. Environ. Psychol.* **2011**, *31*, 207–230. [CrossRef]
35. Luo, S.; Xie, J.; Wang, H.; Wang, Q.; Chen, J.; Yang, Z.; Furuya, K. Natural dose of blue restoration: A field experiment on mental restoration of urban blue spaces. *Land* **2023**, *12*, 1834. [CrossRef]
36. Elsadek, M.; Liu, B.; Xie, J. Window view and relaxation: Viewing green space from a high-rise estate improves urban dwellers' wellbeing. *Urban For. Urban Green.* **2020**, *55*, 126846. [CrossRef]
37. Twedt, E.; Rainey, R.M.; Proffitt, D.R. Beyond nature: The roles of visual appeal and individual differences in perceived restorative potential. *J. Environ. Psychol.* **2019**, *65*, 101322. [CrossRef]
38. Xiang, Y.; Liang, H.; Fang, X.; Chen, Y.; Xu, N.; Hu, M.; Chen, Q.; Mu, S.; Hedblom, M.; Qiu, L.; et al. The comparisons of on-site and off-site applications in surveys on perception of and preference for urban green spaces: Which approach is more reliable? *Urban For. Urban Green.* **2021**, *58*, 126961. [CrossRef]
39. Baron, R.M.; Kenny, D.A. The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *J. Personal. Soc. Psychol.* **1986**, *51*, 1173–1182. [CrossRef]
40. Saunders, C.T.; Blume, J.D. A classical regression framework for mediation analysis: Fitting one model to estimate mediation effects. *Biostatistics* **2018**, *19*, 514–528. [CrossRef]
41. Nutsford, D.; Pearson, A.L.; Kingham, S.; Reitsma, F. Residential exposure to visible blue space (but not green space) associated with lower psychological distress in a capital city. *Health Place* **2016**, *39*, 70–78. [CrossRef]
42. Yin, J.; Ramanpong, J.; Chang, J.; Wu, C.-D.; Chao, P.-H.; Yu, C.-P. Effects of blue space exposure in urban and natural environments on psychological and physiological responses: A within-subject experiment. *Urban For. Urban Green.* **2023**, *87*, 128066. [CrossRef]
43. Liu, F.; Liu, P.; Kang, J.; Meng, Q.; Wu, Y.; Yang, D. Relationships between landscape characteristics and the restorative quality of soundscapes in urban blue spaces. *Appl. Acoust.* **2022**, *189*, 108600. [CrossRef]
44. Ulrich, R.S.; Simons, R.F.; Losito, B.D.; Fiorito, E.; Miles, M.A.; Zelson, M. Stress recovery during exposure to natural and urban environments. *J. Environ. Psychol.* **1991**, *11*, 201–230. [CrossRef]
45. Herzog, T.R. A cognitive analysis of preference for waterscapes. *J. Environ. Psychol.* **1985**, *5*, 225–241. [CrossRef]
46. Pitt, H. Muddying the waters: What urban waterways reveal about bluespaces and wellbeing. *Geoforum* **2018**, *92*, 161–170. [CrossRef]
47. Zhao, J.; Wang, R.; Cai, Y.; Luo, P. Effects of visual indicators on landscape preferences. *J. Urban Plan. Dev.* **2013**, *139*, 70–78. [CrossRef]
48. Lindemann-Matthies, P.; Junge, X.; Matthies, D. The influence of plant diversity on people's perception and aesthetic appreciation of grassland vegetation. *Biol. Conserv.* **2010**, *143*, 195–202. [CrossRef]
49. Luo, S.; Xie, J.; Furuya, K. Assessing the preference and restorative potential of urban park blue space. *Land* **2021**, *10*, 1233. [CrossRef]
50. Gascon, M.; Sanchez-Benavides, G.; Dadvand, P.; Martinez, D.; Gramunt, N.; Gotsens, X.; Cirach, M.; Vert, C.; Luis Molinuevo, J.; Crous-Bou, M.; et al. Long-term exposure to residential green and blue spaces and anxiety and depression in adults: A cross-sectional study. *Environ. Res.* **2018**, *162*, 231–239. [CrossRef]
51. Kanelli, A.A.; Kokkinaki, M.; Sinvare, M.-D.; Malesios, C.; Dimitrakopoulos, P.G.; Kalantzi, O.-I. Keep calm and go out: Urban nature exposure, mental health, and perceived value during the COVID-19 lockdown. *Sustainability* **2023**, *15*, 8831. [CrossRef]
52. Gidlow, C.J.; Jones, M.V.; Hurst, G.; Masterson, D.; Clark-Carter, D.; Tarvainen, M.P.; Smith, G.; Nieuwenhuijsen, M. Where to put your best foot forward: Psycho-physiological responses to walking in natural and urban environments. *J. Environ. Psychol.* **2016**, *45*, 22–29. [CrossRef]
53. Völker, S.; Kistemann, T. The impact of blue space on human health and well-being—Salutogenetic health effects of inland surface waters: A review. *Int. J. Hyg. Environ. Health* **2011**, *214*, 449–460. [CrossRef] [PubMed]
54. Liu, S.; Lai, S.-Q.; Liu, C.; Li, J. What influenced the vitality of the waterfront open space? A case study of huangpu river in Shanghai, China. *Cities* **2021**, *114*, 103197. [CrossRef]

55. Fan, Y.; Kuang, D.; Tu, W.; Ye, Y. Which spatial elements influence waterfront space vitality the most?—A comparative tracking study of the maozhou river renewal project in Shenzhen, China. *Land* **2023**, *12*, 1260. [CrossRef]
56. Zhao, W.; Li, X.; Zhu, X.; Ye, H.; Xu, H. Restorative properties of green sheltered spaces and their morphological characteristics in urban parks. *Urban For. Urban Green.* **2023**, *86*, 127986. [CrossRef]
57. Collins, D.; Kearns, R. Ambiguous Landscapes: Sun, Risk and Recreation on New Zealand Beaches. In *Therapeutic Landscapes*; Routledge: London, UK, 2007. [CrossRef]
58. Zheng, H.; Wu, B.; Wei, H.; Yan, J.; Zhu, J. A quantitative method for evaluation of visual privacy in residential environments. *Buildings* **2021**, *11*, 272. [CrossRef]
59. Kim, J.; de Dear, R. Workspace satisfaction: The privacy-communication trade-off in open-plan offices. *J. Environ. Psychol.* **2013**, *36*, 18–26. [CrossRef]
60. Asgarzadeh, M.; Lusk, A.; Koga, T.; Hirate, K. Measuring oppressiveness of streetscapes. *Landsc. Urban Plan.* **2012**, *107*, 1–11. [CrossRef]
61. Bratman, G.N.; Hamilton, J.P.; Hahn, K.S.; Daily, G.C.; Gross, J.J. Nature experience reduces rumination and subgenual prefrontal cortex activation. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 8567–8572. [CrossRef]
62. Asakawa, S.; Yoshida, K.; Yabe, K. Perceptions of urban stream corridors within the greenway system of Sapporo, Japan. *Landsc. Urban Plan.* **2004**, *68*, 167–182. [CrossRef]
63. Zhao, J.; Luo, P.; Wang, R.; Cai, Y. Correlations between aesthetic preferences of river and landscape characters. *J. Environ. Eng. Landsc. Manag.* **2013**, *21*, 123–132. [CrossRef]
64. Luo, S.; Xie, J.; Furuya, K. Effects of perceived physical and aesthetic quality of urban blue spaces on user preferences-A case study of three urban blue spaces in Japan. *Heliyon* **2023**, *9*, e15033. [CrossRef]
65. Bell, S.L.; Foley, R.; Houghton, F.; Maddrell, A.; Williams, A.M. From therapeutic landscapes to healthy spaces, places and practices: A scoping review. *Soc. Sci. Med.* **2018**, *196*, 123–130. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

*Article*

# Protecting Rural Large Old Trees with Multi-Scale Strategies: Integrating Spatial Analysis and the Contingent Valuation Method (CVM) for Socio-Cultural Value Assessment

**Na Yao [1], Chenxi Gu [1], Jinda Qi [2], Shigang Shen [1,3], Bo Nan [1] and Hongjie Wang [1,4,*]**

[1] Hebei Key Laboratory of Close-to-Nature Restoration Technology of Wetlands, School of Eco-Environment, Hebei University, Baoding 071002, China; yaona@hbu.edu.cn (N.Y.); guchenxi@stumail.hbu.edu.cn (C.G.); shensg@hbu.edu.cn (S.S.); nanbo@hbu.edu.cn (B.N.)
[2] Department of Architecture, College of Design and Engineering, National University of Singapore, Singapore 117575, Singapore; jindaqi@nus.edu.sg
[3] Key Laboratory of Analytical Science and Technology of Hebei Province, College of Chemistry and Materials Science, Hebei University, Baoding 071002, China
[4] College of Life Science, Hebei University, Baoding 071002, China
* Correspondence: wanghj@hbu.edu.cn

**Abstract:** Governments are faced with the unique challenge of implementing large-scale and targeted protection against the global decline of large old trees. Incorporating socio-cultural values and encouraging public involvement are important parts of conservation policy. However, current studies on the socio-cultural valuation of large old trees are still limited, and how rural residents perceive the human-related value of large old trees remains largely unknown. Using a quantitative, spatial analysis and the contingent valuation method (CVM), we tried to explore a multi-scale socio-cultural valuation and protection framework based on a case study of Baoding City and Xiongan New Area in North China. The results showed that (1) the scattered large old trees in the study area were generally at a relatively younger stage, showing normal growth performance but having poor living environments. Some 96.99% of the trees resided in the countryside. Their distribution showed an agglomerative pattern with several clusters. (2) The species richness was relatively lower than that reported in urban areas. The species diversity had an obvious high–low gradient from the mountain to plain areas. Most endemic species were found in habitats of the village fringe (VF) and government/community/institutional ground (GC). (3) The mean willingness to pay (WTP) for the socio-cultural value of scattered large old trees was CNY 132.48 per year per person (1 US dollar equals about 7.2 CNY) of all the respondents, and CNY 84.30 per year per person with regard to farmers, which is relatively higher than that reported in large cities. (4) Economic income, gender, age, education level, place of residence, diameter at breast height, and tree habitat were factors that significantly influenced the WTP, among which economic income was the most significant. (5) The importance ranking of socio-cultural value connotations perceived by rural residents was as follows: spiritual attachment and homesickness > fengshui > social bond > witnessing history > education > creative inspiration. (6) The annual gross value was estimated to be CNY 349 million in the study area, and CNY 169,500 for a single tree on average. Based on the case study, a conceptual framework for socio-cultural value assessment and multi-scale protection of large old trees was proposed, which can provide references for the improvement of current conservation policies from both quantitative and qualitative perspectives, and give insights into rural revitalization strategies in China.

**Keywords:** large old trees; socio-cultural value; contingent valuation method; willingness to pay; spatial analysis; biocultural diversity

**Citation:** Yao, N.; Gu, C.; Qi, J.; Shen, S.; Nan, B.; Wang, H. Protecting Rural Large Old Trees with Multi-Scale Strategies: Integrating Spatial Analysis and the Contingent Valuation Method (CVM) for Socio-Cultural Value Assessment. *Forests* **2024**, *15*, 18. https://doi.org/10.3390/f15010018

Academic Editor: Pablo Vergara

Received: 16 November 2023
Revised: 17 December 2023
Accepted: 18 December 2023
Published: 20 December 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

As "life-history lottery winners", large old trees have shown strong adaptiveness to environmental changes, being the most iconic organisms of human settlements, important an-

chors of biodiversity networks, and a substantial inheritance of ecological civilizations [1–4]. However, their global decline has been a prominent issue that needs to be addressed appropriately [5]. While clustered large old trees are mainly found as small natural features in primitive forests, scattered large old trees usually occur in human-dominated landscapes as spatially isolated individual trees. In comparison, scattered large old trees are more susceptible to a range of threats such as climate change, diseases, pests, natural disasters, poor living environments, and human disturbance [6–8]. Therefore, targeted fine-scale strategies are required for the conservation and management of this ancient natural heritage [6,9,10].

Identifying the location and growing conditions of large old trees is vital work for their strategic management. Once this information is acquired, specific measures can be taken for protection, for example, setting up guardrails and identity cards, conducting rejuvenation and pest control, etc. [11]. However, these activities are challenging for the government due to the scattered distribution and complicated situations of individual trees. Tree growth stress and influential factors need to be figured out one by one. Another way that trees may be protected is at the community level, by exploring their distribution patterns and driving factors, setting aside large reserves, and paying attention to the dynamic of key influential factors to conduction strategic protection. Such explorations have been made frequently in the literature, at different scales such as worldwide [12], nationwides [7,13], citywide [14,15], within forest parks [16], within ethnic minority settlements [17,18], and within agricultural landscapes [19], which and have provided important information for understanding and conserving of large old trees. For example, it was revealed that the distribution density of scattered large old trees in China was positively correlated with mean annual rainfall and human population density, while the distribution density of clustered large old trees was negatively influenced by human population density [7]. A few studies conducted within large- or medium-size cities in China found that the spatial distribution of large old trees showed a state of "scattered and multiple clusters" [14,20], and districts with more scenic resort and historic site (SRHS) and higher gross domestic product (GDP) tend to accommodate more heritage trees [21].

In addition to governmental protection actions, encouraging public support and participation by incorporating socio-cultural values of the large old trees is an important part of conservation policy, because it may strengthen the inherent motivation for conservation by highlighting the potential synergies in fostering biocultural diversity and natural capital circulation [17,22,23]. The concept of "socio-cultural values" is within the ecosystem services (ES) assessment framework, which consists of three domains of ecological, economic, and socio-cultural services [24,25]. The socio-cultural values provided by large old trees include aesthetic, symbolic, religious, and historic aspects [23], as well as "Fengshui", which in the Chinese tradition has symbolic meanings of health, longevity, flourishing populations, fortune, and wealth [26]. For example, a cultural mechanism was developed in Central Himalaya through an intelligent practice of locating protected tree species within sacred boundaries [27]. In this way, religious philosophy can contribute as a valuable tool for bioresources' conservation.

The contingent valuation method (CVM) is a widely used nonmarket valuation method, especially in the area of environmental economics [28,29]. By creating a questionnaire survey to assess the willingness to pay (WTP) of respondents, information about the preference-related value of non-marketed environmental goods (the socio-cultural services provided by scattered large old trees, in this case) can be generated. For example, Chen [30] conducted contingent valuation and discovered that the mean public WTP for conserving heritage trees in Guangzhou, south China, in 2013 was about CNY 24.67 per year, and CNY 31.26 per year per household (1 US dollar equals about 7.2 CNY) for common and rare heritage tree species, respectively, and economic income was the only significant factor influencing WTP; Lin et al. [31] revealed that the WTP per person for the 1000-year-old tree of Qiedong-Wang-Gong in Taichung City, Taiwan was NTD 246.80 (about CNY 55.96) CNY per year when protest responses were excluded, and that middle-aged people were likely to pay more than others. Son et al. [32] estimated that the total value of an old giant tree of

Zelkova Serrata in Gyeongju of Korea was KRW 491,503,300 (about CNY 2,660,658), including economic, aesthetic, ecological, scientific, and social value; Wang et al. [33] followed the millennium ancient banyan in Fuzhou National Forest Park, and found that its economic, historical, cultural, social and ecological value was evaluated to be CNY 1.9 billion.

By clarifying the interior value of large old trees, social concern and conservation policies such as ecological compensation and value realization of gross ecosystem product (GEP) can be promoted [34,35]. However, studies on the socio-cultural valuation of large old trees are still limited, and the factors influencing public WTP for large old tree conservation have rarely been explored. Moreover, current studies in this field have mostly been conducted in urban areas, whereas very few investigations have focused on the socio-cultural value perception of rural residents, especially farmers. Hartel et al. [36] assessed the importance of different values of scattered trees (mature and old) from oak wood pastures appreciated by traditional farmers in a rural region of Transylvania (Romania), but monetary valuation was not conducted. In China, according to the results of the second national survey of ancient and famous tree resources, among the 5.08 million old trees of China, 95.15% of them were distributed in rural areas [37]. It is therefore significant to fill the gap of how rural residents, especially Chinese farmers in rural areas, perceive the socio-cultural value of scattered large old trees.

This paper reports the findings of an integrated study of the spatial distribution and contingent socio-cultural valuation of scattered large old trees. The study is unique from previous works, as it was conducted at multiple scales, intending to support a multi-scale conservation strategy of rural large old trees from both quantitative and qualitative perspectives. We focused on a typical area in North China of the ancient city of Baoding and the adjacent national economic zone of Xiongan New Area. Our study (1) analyzed the quantitative characteristics and distribution pattern of scattered large old trees in the study area; (2) investigated public WTP for the socio-cultural value of scattered large old trees and discussed the influencing factors; and (3) estimated the multi-scale socio-cultural value of scattered large old trees. The results can contribute to providing a reference for a multi-scale strategy of large old tree conservation with up-down hierarchical and targeted protection, as well as bottom-up socio-cultural value inspiration and realization.

## 2. Materials and Methods

### *2.1. Study Area*

Baoding City and Xiongan New Area is located in the northern part of the North China Plain and the central part of the Beijing–Tianjin–Hebei (BTH) region, spanning a 114°32′–116°20′ East longitude and a 38°14′–39°36′ North latitude, with a total area of about 21,089 $km^2$ (Figure 1). The overall topography is characterized by a slope from northwest to southeast, featuring middle mountains, low mountains and hills, plains, and puddle precipitation areas. The Baiyangdian Lake, which is the largest freshwater lake in the North China Plain, lies in the east. The study area is in the temperate continental monsoon climate zone characterized by four distinct seasons, the average annual temperature is about 12.6 °C, and the average annual precipitation is around 550 mm. The permanent resident population of the study area was about 11.44 million in 2020 [38].

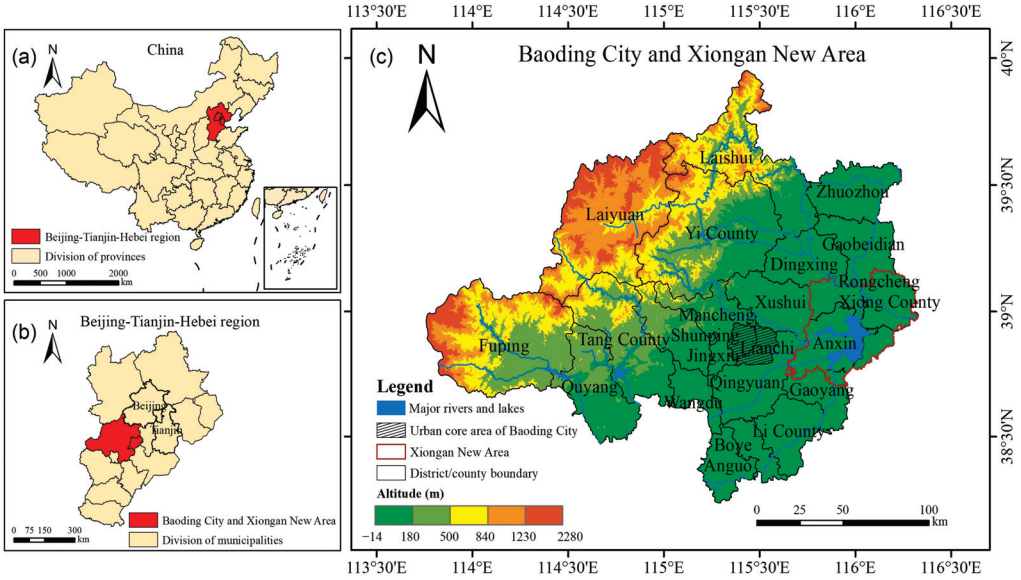



**Figure 1.** Overview of the study area: (**a**) Location of the Beijing–Tianjin–Hebei (BTH) region in China; (**b**) location of Baoding City and Xiongan New Area in the BTH region; (**c**) the altitude and administrative division of districts and counties of Baoding City and Xiongan New Area.

Baoding is a famous historical city with a history of more than 3000 years of civilization. It is the birth and enthronement place of the ancient Emperor Yao [39], and was the cradleland of the Yan dynasty during the Warring States period in ancient China [40]. In the modern era, Baoding has played an empirical geographic role in safeguarding the capital of Beijing. The establishment of Xiongan New Area in 2017 was a major decision made by the Communist Party of China (CPC) Central Committee, with Comrade Xi Jinping at its core, to push forward the synergistic development of the BTH region and to ease the non-capital functions of Beijing. Its planning scope involves the three counties of Xiong County, Rongcheng, and Anxin, which were formerly administrated by Baoding City, as well as part of the surrounding areas formerly administrated by Cangzhou City. We neglected the Cangzhou part in this study, as the census data of large old trees were unavailable in this area.

### *2.2. Data Collection*

#### 2.2.1. The Census Data

In China, two rounds of the national survey of ancient and famous tree resources were conducted in 2001 and 2015, respectively. Normative guidance for the survey includes the Chinese government's national-level document "Technical Guidelines for the Document Establishment of a General Survey of National Ancient and Famous Trees", issued in 2001, as well as the "Technical regulation for the Surveying of Old and Notable Trees", released in 2016 [37,41]. According to the above guidance and relevant articles [10,17,21], a scattered large old tree in this study was defined as a tree or shrub over 100 years of age and distributed in human-dominated landscapes (excluding national forest farms, natural forests, and protected areas). Before our study, the Baoding Forestry Department of the Natural Resources and Planning Bureau had carried out a second round of investigation of all the large old trees in the city. Investigation items included geographical location, elevation, habitat, ownership, tree species, tree age, diameter at breast height (DBH), canopy size, and growth potential, etc. The survey tools included a GPS, compass meter, tree altimeter, measuring ropes, perimeter rulers, and cameras. Tree ages were generally identified based on historical literature records or legends provided by local elders, or by empirical estimation according to tree growth parameters. Based on tree ages, three categories were classified for protection, i.e., tier 3 (100~299 years of age), tier 2 (300~499 years of age), and tier 1 ($\geq$500 years of age).

The census data of scattered large old trees in this study were derived from the official website of the Natural Resources and Planning Bureau of Baoding in May 2022 (https://zrgh.baoding.gov.cn/ (accessed on 21 May 2022)), which came from the second round of national ancient trees' investigation. The original census data were recorded in the form of investigation reports on each administrative county/district. We converted the database into point elements in ArcGIS 10.2. A geographic database including the census data of scattered large old trees and other relevant spatial data from the study area was established using the WGS_1984_Web_Mercator_Auxiliary_Sphere projection in ArcGIS 10.2, Environmental Systems Research Institute (Esri), Inc., Redlands, CA, USA.

Township-level population data of Baoding City and Xiongan New Area was obtained from the Seventh National Population Census Bulletin. To conduct village-level calculations, a publicly available China Land Cover Dataset (CLCD) land cover product [42] (2020) from Wuhan University was used. As previous researchers found that impervious surfaces had a strong linear relationship with population [43], we estimated the village-level population by distributing the total township number to each administrative village/urban street according to the weighted impervious surface area calculated based on the CLCD land cover product.

#### 2.2.2. Questionnaire Survey

Following standard guidelines for the CVM [28], we designed a questionnaire to generate information about the perceived socio-cultural value of scattered large old trees oflocal residents (Table S1). The questionnaire starts with a brief introduction to the survey, and the main section consists of three parts. The first part gathers the respondents' demographic and socio-economic characteristics, including gender, age, occupation, education level, and personal monthly fixed income. The second part investigates the respondents' WTP for the socio-cultural value of scattered large old trees by listing six connotations used to explain what socio-cultural value means, including social bond, spiritual attachment and homesickness, fengshui, witnessing history, creative inspiration, and education [23,44,45] (Table 1). If the respondents had difficulties giving answers, semi-structured interviews could occasionally be conducted by asking about his/her life-related experiences or stories of the large old trees to remind the respondents. The third part of the survey pertains to the willingness to allocate the above amount of WTP to the six types of socio-cultural values, which represents the degree of recognition and appreciation of respondents for each of the six types of socio-cultural value connotation.

**Table 1.** Classification and connotations of the socio-cultural value of scattered large old trees.

| Classification | Connotations |
| --- | --- |
| Social bond | The large old trees can facilitate social bonds by providing a place or landmark to get together, enjoy shade, and communicate [46]. |
| Spiritual attachment and homesickness | The large old trees can witness the growth of generations and protect them like divinities, bringing spiritual attachment and nostalgia to people who leave their hometown [47]. |
| Fengshui | The large old trees bear "fengshui" symbolism, which has the symbolic meanings of health, longevity, blessings and good fortune [44]. |
| Witnessing history | The large old trees are "living relics" that have witnessed the local history, and there are some historical stories associated with them [48]. |
| Creative inspiration | The large old trees can bring cultural creativity or inspiration that can appeal to our aesthetic sentiments, for example, drawing, photographing, and short video creation on social media, etc. [49]. |
| Education | The large old trees can be used as a good subject for conducting scientific research, popular science activities, or liberal education [22]. |

Considering the workload and disparity of socio-cultural backgrounds in the study area, we selected Laiyuan County, the urban core area of Baoding City, and Xiongan New Area as three typical territories on which to conduct a random sampling of scattered large old trees for the questionnaire survey. A total of 56 large old trees were randomly chosen in ArcGIS 10.2 using a tool for the random sampling of point elements (Figure S1, 40 in Laiyuan County, 2 in the urban core area of Baoding City, and 14 in Xiongan New Area). These 56 trees are intended to represent the total 2062 scattered large old trees for the investigation of the socio-cultural perceptions of local residents. The field investigation was conducted in October of 2022, and April to May of 2023. For each visited tree, 15~25 residents nearby were asked to fill out the questionnaires. A total of 1114 respondents were approached, and it took about 15~20 minutes for each respondent to complete the questionnaire on average. After investigation, the collected questionnaires were visually screened to ensure integrality and reliability.

### 2.3. Statistical and Spatial Analysis of the Scattered Large Old Trees

Firstly, descriptive statistics of the species' composition and growth indicators were obtained to figure out the structural background of the large old tree community. Adjusted species richness [50] was calculated using the following equation:

$$D = \frac{N}{\ln A} \tag{1}$$

where D is the modified species diversity index, N is the number of total species for a given region, and A is the area of the region.

Secondly, three indicators of the nearest neighbor index, kernel density estimation, and Lorenz curve were calculated to reveal the distribution pattern of the scattered large old trees at the county/district level.

The nearest neighbor index (R) is defined as the ratio of the actual nearest neighbor distance to the theoretical nearest neighbor distance [14]. Here, it was used to discover the distribution patterns (including random, uniform, or cohesive) of scattered large old trees in Baoding City and Xiongan New Area. "Average Nearest Neighbor" in ArcGIS Toolbox 10.2 was used for calculation, and the formula is as follows [14]:

$$R = \frac{\overline{R_i}}{\overline{R_E}} \tag{2}$$

$$\overline{R}_E = \frac{1}{2\sqrt{m/A}} = \frac{1}{2\sqrt{D}} \tag{3}$$

where, $\overline{R_i}$ represents the average of the distance between each point and its nearest neighbor; $\overline{R_E}$ is the theoretical nearest neighbor distance when the point-like elements are randomly distributed; m represents the number of point elements; A represents the study area; and D represents the number of point elements per unit area. When R = 1, the point elements tend to be randomly distributed; when R > 1, the point elements tend to be uniformly distributed; when R < 1, the point elements tend to be cohesively distributed.

The kernel density analysis is often used to estimate the unknown density function, which can reveal the density of the neighborhood around each point element [51,52]. The higher its spatial point density, the greater the probability of occurrence in this spatial region, which can visually reflect the degree of concentration and dispersion of large old trees. The "Kernal Density Estimation" function in ArcGIS Toolbox 10.2 was used in this study, and the formula is as follows [51]:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x - x_i}{h}\right) \tag{4}$$

where k is the kernel density function; h is the bandwidth; n is the number of points in the range of values; and $(x - x_i)$ denotes the distance from the valuation point x to event $x_i$.

The Lorenz curve method measures fairness, which uses a curve drawn by frequency accumulation to portray its degree of inequality (concentration or dispersion) [53]. In this study, the Lorenz curve was plotted in Excel. The degree of deviation between the Lorenz curve and the uniform distribution line was used to determine whether the distribution of scattered large old trees in each district and county was balanced.

Thirdly, the distribution of scattered large old trees at the habitat level was analyzed in a combined consideration of the census data, field investigation, and literature reviews. The habitats of scattered large old trees in the study area were classified into seven categories, including government/community/institutional ground (GC), residential district (RD), temple (TE), village fringe (VF), scenic resort/historic site (SRHS), hillside (HI), and cemetery (CE). The number of trees in each habitat was calculated.

Fourthly, a downtrend correspondence analysis was conducted to demonstrate species distribution properties. DCA is derived from CA (correspondence analysis). But DCA eliminates the "arch effect" by ordering old growth habitats so that similar species are close together and dissimilar species are farther apart within the same sample, thus revealing the ecological relationships between species and their environments [21,41,54]. The results of the DCA analysis plot the species or environment on two axes, each corresponding to a dimension in space [55]. In this study, we conducted the DCA analysis using the Canoco 5.0 software, Microcomputer Power Corporation, Ithaca, NY, USA. A counties/districts $\times$ species matrix and a habitats $\times$ species matrix were established to analyze the species distribution of scattered large old trees in the study area.

### *2.4. Contingent Valuation and Driving Factor Analysis*

Based on the results of the questionnaire survey, a comparative analysis of mean WTP and the significance of differences within groups of respondents from different backgrounds was conducted. Meanwhile, the corresponding divided WTP of each socio-cultural connotation was also analyzed in groups. The descriptive statistical analysis of the data was conducted using IBM SPSS Statistics 26, International Business Machines Corporation, Armonk, NY, USA.

Three regression models including Model 1 (ordered logit), Model 2 (ordered probit), and Model 3 (random forest) were tested to explore the effects of different factors on residents' WTP for the socio-cultural value of scattered large old trees. A total of 12 independent variables were selected for model analysis, including demographic characteristics of gender, age, education level, occupation, personal monthly fixed income, and place of residence, as well as tree characteristics of species, grade of tree age, height, diameter at breast height (DBH), canopy size, and habitat. In addition to three continuous variables of tree height, DBH, and canopy size, the description and coding of nine categorical variables with a range of attribution levels can be found in Table S2.

The ordered logit and probit models are both regression models for an ordinal response variable based on cumulative probabilities [56]. The difference between the two models is that the random disturbance of the logit model is assumed to be a cumulative standard logistic distribution, while the probit model is assumed to be a cumulative standard normal distribution. Both of the two models have been widely used for influential factor studies [57,58]. It has been observed in a former study that the effect of excluding protest responses on the economic valuation of large old trees is relatively low [59]. Therefore, samples of WTP = 0 in this study were excluded during the regression analysis, considering that only 2.31% of the respondents gave protest responses or had no economic ability during the survey. The dependent variable of WTP was classified into six categories of CNY 1~5, 5~10, 10~50, 50~100, 100~500, and >500, numbered from 1 to 6. The two models of ordered logit and probit were established using Stata 17 software.

Random forest is a flexible, easy-to-use machine learning algorithm that can be used for classification and regression tasks, and is one of the most commonly used algorithms in influential factors studies [60,61]. Random forest randomly selects some of the variables each time it creates a model, so the correlation between variables has less impact on model accuracy. In this study, it was used to further explore the importance of influential factors in determining residents' WTP. The simulation was conducted using the "randomForest" function of the "randomForest" package in R for windows 4.2.2. The importance of independent variables can be revealed via the node impurity among the modeling results, which is weighted by the probability of reaching that node [62].

### *2.5. Multi-Scale Socio-Cultural Value Assessment*

Based on our survey data, an average WTP/person/tree can be generated. We assumed that the socio-cultural value provided by the scattered large old trees was within the village/urban street area wherein they were located. This is because most of the scattered large old trees in the study area were located in the countryside, and 90.9% of the trees were collectively owned by the village (64.1%) or state-owned (26.8%), while the remaining 9.1% were privately owned. So, firstly, we calculated the village-level gross socio-cultural value (V) according to the following formula:

$$V = \overline{WTP} \times P \times n \quad (5)$$

where $\overline{WTP}$ is the average willingness to pay; P is village population; and n is the number of scattered large old trees in that administrative village/urban street.

The $\overline{WTP}$ in this study was only generated in the three districts of Laiyuan County, the urban core area of Baoding City, and Xiongan New Area. The social economic development level of the left counties was more similar to that of Laiyuan County, and the $\overline{WTP}$ of Laiyuan was used as a substitute in the left areas.

Secondly, township-level gross value was collected based on the above results; thirdly, county/district-level gross values were further generated. The distribution of the multi-scale socio-cultural value of scattered large old trees was plotted using ArcGIS 10.2.

## 3. Results

### *3.1. Community Characteristics and Spatial Distribution of the Scattered Large Old Trees in the Study Area*

#### 3.1.1. Community Characteristics

A total of 2062 scattered large old trees were identified in Baoding City and Xiongan New Area, belonging to 52 species, 35 genera, and 22 families (Table 2). The ratio of evergreen species and deciduous species was 7:45, and the adjusted species richness was 5.22. At the family level, *Pinaceae*, *Cupressacea*, and *Papilionacea* were the most abundant, accounting for 22.36%, 14.45%, and 14.21% of the total scattered large old trees, respectively. At the genus level, *Pinus*, *Sophora*, and *Platycladus* appeared the most frequently, accounting for 21.77%, 14.21%, and 14.11% of the total, respectively. At the species level, *Pinus tabulaeformis* Carr., *Sophora japonica* L., *Platycladus orientalis* (L.) Franco, *Diospyros kaki* Thun., and *Ziziphus jujuba* Mill. ranked at the top, accounting for 21.29%, 14.21%, 14.11%, 12.17%, and 11.01% of the total, respectively (Tables S3 and S4).

**Table 2.** Family ranking of scattered large old trees in Baoding City and Xiongan New Area.

| Rank | Family | Number of Genera | Number of Species | Number of Trees | Percentage of Trees (%) |
|---|---|---|---|---|---|
| 1 | *Pinaceae* | 2 | 4 | 461 | 22.36 |
| 2 | *Cupressaceae* | 3 | 4 | 298 | 14.45 |
| 3 | *Papilionaceae* | 1 | 1 | 293 | 14.21 |
| 4 | *Ebenaceae* | 1 | 2 | 256 | 12.42 |
| 5 | *Rhamnaceae* | 1 | 2 | 231 | 11.20 |
| 6 | *Rosaceae* | 3 | 5 | 215 | 10.43 |
| 7 | *Fagaceae* | 2 | 5 | 99 | 4.80 |
| 8 | *Salicaceae* | 2 | 5 | 42 | 2.04 |
| 9 | *Anacardiaceae* | 1 | 1 | 29 | 1.41 |
| 10 | *Ulmaceae* | 3 | 3 | 29 | 1.41 |
| 11 | *Juglandaceae* | 1 | 3 | 24 | 1.16 |
| 12 | *Leguminosae* | 3 | 3 | 20 | 0.97 |
| 13 | *Bignoniaceae* | 1 | 1 | 16 | 0.78 |
| 14 | *Oleaceae* | 3 | 4 | 12 | 0.58 |
| 15 | *Moraceae* | 1 | 1 | 12 | 0.58 |
| 16 | *Aceraceae* | 1 | 2 | 10 | 0.48 |
| 17 | *Simaroubaceae* | 1 | 1 | 5 | 0.24 |
| 18 | *Ginkgoaceae* | 1 | 1 | 4 | 0.19 |
| 19 | *Meliaceae* | 1 | 1 | 3 | 0.15 |
| 20 | *Elaeagnaceae* | 1 | 1 | 1 | 0.05 |
| 21 | *Solanaceae* | 1 | 1 | 1 | 0.05 |
| 22 | *Sapindaceae* | 1 | 1 | 1 | 0.05 |
| 23 | Total | 35 | 52 | 2062 | 100.00 |

As shown in Table 3, most of the scattered large old trees in the study area were 10~20 m in height, lower than 1 m in DBH, less than 10 m in canopy size, and aged 100~299 years in Tier 3. The growth performances were generally normal, but the living environments were not promising, with more than 80% of the trees more or less living under environmental stress. Some examples of these stresses are extensive impervious cover around the trees, human disturbance, severe tree diseases, or natural damage without rejuvenation strategies, which represent a challenging management task for the future.

**Table 3.** Growth conditions of scattered large old trees in Baoding City and Xiongan New Area.

| Statistical Items | Quantitative/Qualitative Categories | Number of Trees | Percentage of Trees (%) |
|---|---|---|---|
| Tree height | ≤10 m | 943 | 45.73 |
| | 10~20 m | 1008 | 48.88 |
| | ≥20 m | 111 | 5.38 |
| Diameter at breast height (DBH) | <1 m | 1905 | 92.39 |
| | ≥1 m | 157 | 7.61 |
| Canopy size | ≤10 m | 1370 | 66.44 |
| | 10~20 m | 642 | 31.14 |
| | ≥20 m | 50 | 2.42 |
| Grade of tree age | Tier 1 (≥500 years) | 109 | 5.29 |
| | Tier 2 (300~499 years) | 173 | 8.39 |
| | Tier 3 (100~299 years) | 1780 | 86.32 |
| Growth potential | Normal | 1977 | 95.88 |
| | Weak | 73 | 3.54 |
| | Endangered | 12 | 0.58 |
| Living environment | Poor | 31 | 1.50 |
| | Fair | 1649 | 79.97 |
| | Moderate | 382 | 18.53 |

3.1.2. Spatial Distribution

The result of nearest-neighbor index calculation of scattered large old trees in the study area is illustrated in Figure 2. It shows that the nearest-neighbor ratio was 0.330784 (less than 1), which means the distribution pattern of scattered large old trees in the study area was agglomerative. The *p*-value and z-score manifested that the probability of randomly generating this clustering pattern was less than 1%.

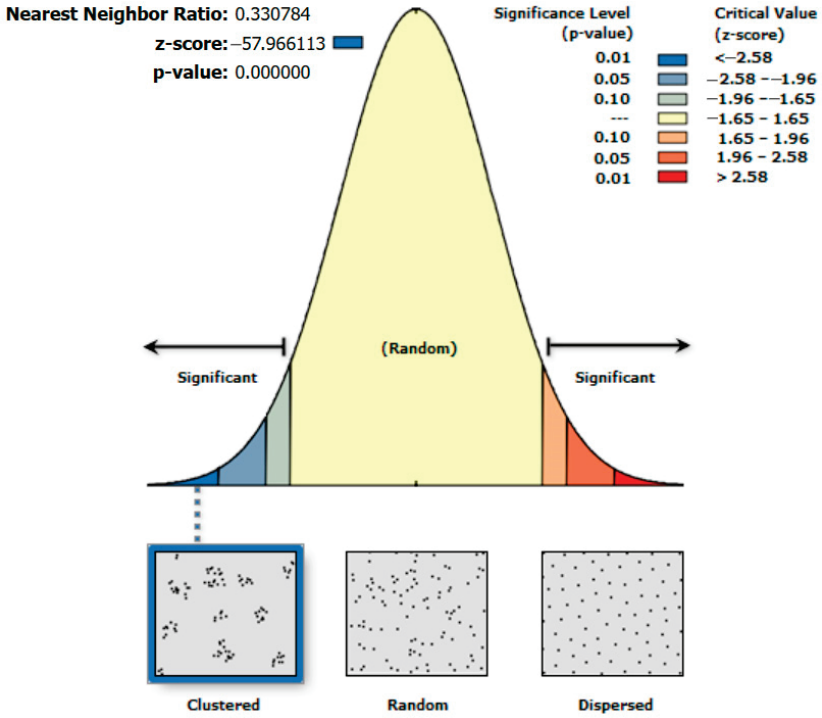



**Figure 2.** Nearest neighbor index of scattered large old trees in Baoding City and Xiongan New Area.

The distribution pattern of scattered large old trees in the 23 counties/districts of Baoding City and Xiongan New Area is further demonstrated in Figure 3. The kernel density estimation result within a 30 km search radius is shown in Figure 3a. We found a high-density agglomeration center in Yi County, with a kernel density of 0.27–0.40 plants/km$^2$, and three sub-agglomerations in Laiyuan County, Quyang County, and Xiong County, with a kernel density of 0.09–0.15 plants/km$^2$, showing a significant regional difference in the abundance of scattered large old trees. The hot spot in Yi County was located at the Western Tombs of Qing Dynasty, which is a famous scenic resort and historic site; therefore, more heritage trees were protected and reserved at this place.

The Lorenz curve and tree density in each county/district are displayed in Figure 3b. These show that the deviation of Lorenz from the uniform distribution line was obvious, indicating that there was an uneven distribution of scattered large old trees. Among them, Yi County, Quyang County, Laiyuan County, and Xiong County had more heritage trees, with a combined proportion of 71.78%. However, Yi County, Xiong County, and Lianchi District ranked the highest in tree density, at 0.20, 0.19, and 0.17 trees/km$^2$, respectively. The mean density of scattered large old trees in the whole study area was 0.10 trees/km$^2$.

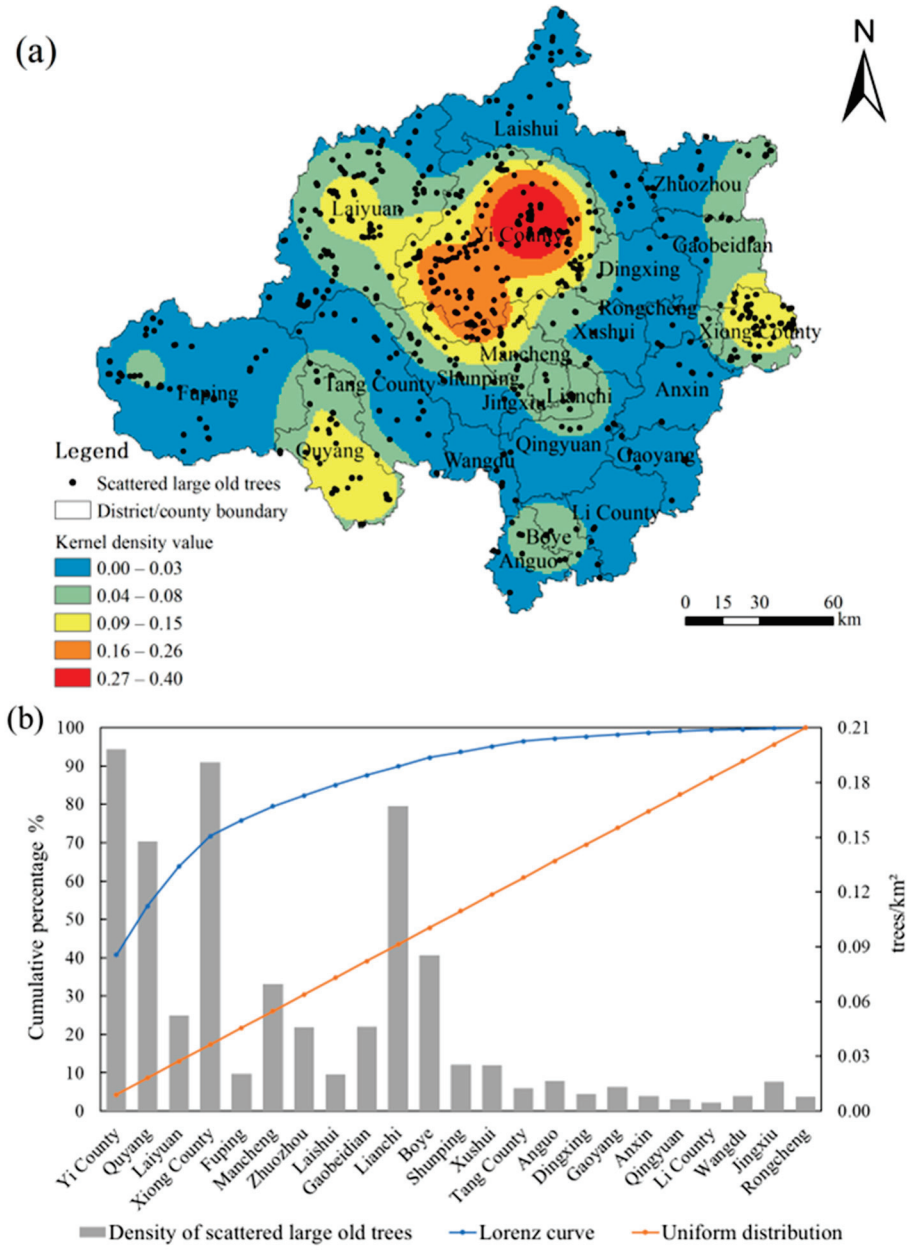



**Figure 3.** Distribution pattern of scattered large old trees in the 23 counties/districts of Baoding City and Xiongan New Area: (**a**) kernel density estimation; (**b**) Lorenz curve and regional tree density.

According to the census data, 96.99% of the scattered large old trees in the study area reside in the countryside. As displayed in Figure 4, the greatest number of scattered large old trees were found in the village fringe (VF), government/community/institutional ground (GC), and scenic resort/historic sites (SRHS), accounting for 35.2%, 21.1%, and 19.7%, respectively; meanwhile, the lowest number were found in cemetery in folk (CE), residential district (RD), and temple (TE). The distribution seemed to be negatively corelated with the degree of privacy of the habitats.

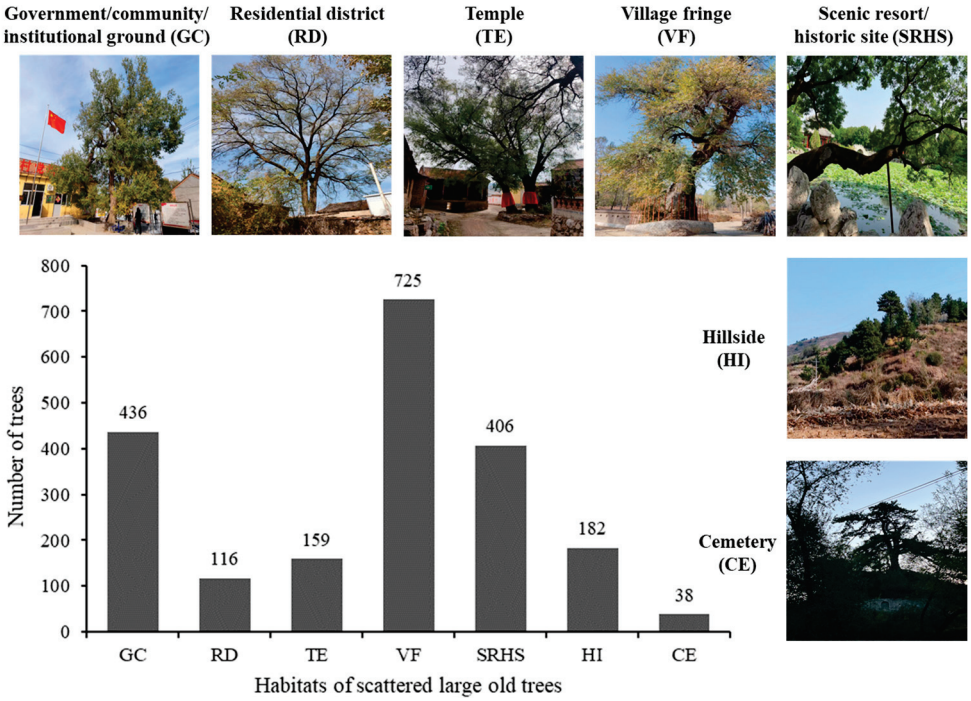
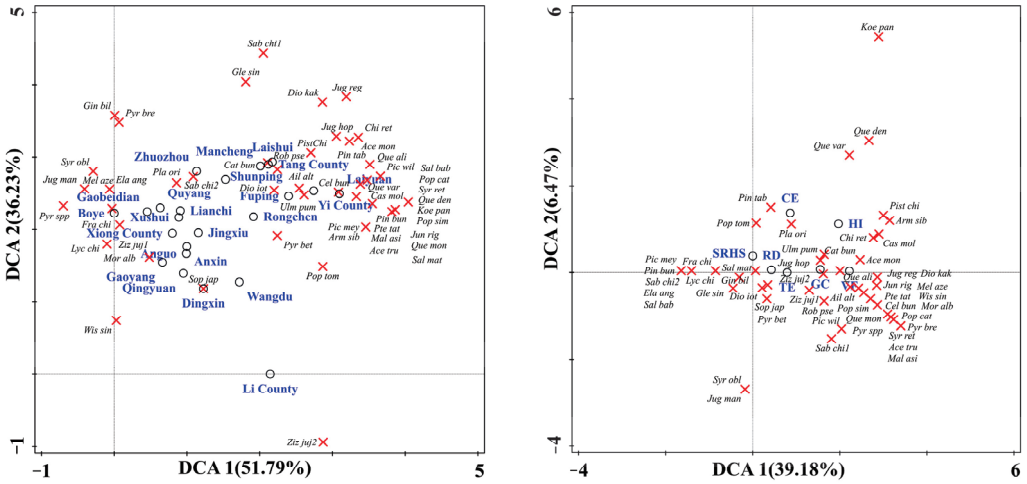



**Figure 4.** Habitat distribution of scattered large old trees in Baoding City and Xiongan New Area. (photos taken by the authors during the survey).

The species distribution of scattered large old trees by districts/counties in the study area is shown in Figure 5a, with DCA explaining 88.03% of the total variance (51.79% for axis 1 and 36.23% for axis 2). Overall, the distribution varied considerably among the 23 districts/counties, and had an obvious gradient differentiation from the mountain to plain areas. Fewer species were found in the plain areas probably due to a lower tree density. Moreover, it was found that only one tree species, *Sophora japonica* Linn., appeared in all of the 23 districts and counties. In addition, 70% of all the districts or counties had their unique tree species, among which Yi County had the most, including *Acer trumcalum, Armeniaca sibirica* (L.) Lam., *Castanea mollissima* BL., and another five species, followed by Laiyuan, with *Juniperus rigida* S. et Z., *Koelreuteria Paniculata* Laxm., *Populus cathayana* Rehd., and four other species.

The species distribution of scattered large old trees by habitats is shown in Figure 5b, with DCA explaining 45.65% of the total variance (39.18% on axis 1 and 6.47% on axis 2). More species appeared in the village fringe (VF) and on government/community/institutional ground (GC), and government/community/institutional ground (GC) had the most unique tree species, including *Juglans hopeiensis* Hu, *Juniperus rigida* S. et Z., *Melia azedarach* Linn., *Pteroceltis tatarinowii* Maxim., *Wisteria sinensis* (Sims) Sweet and *Ziziphus jujuba* Mill. var. spinosa (Bunge) Hu ex H.F. Chow. *Pinus tabulaeformis* Carr., *Platycladus orientalis* (Linn.) Franco and *Sophora japonica* Linn. were found in all seven habitats. Two unique species were found in residential districts (RD), temples (TE), scenic resort/historic sites (SRHS), and the village fringe (VF), respectively, and only one unique species of *Koelreuteria paniculata* Laxm was found in hillside (HI) habitat. *Pinus tabulaeformis* Carr. was the dominant species of scenic resort/historic sites (SRHS) and cemeteries (CE); and *Platycladus orientalis* (Linn.) Franco. was the dominant species in the temples (TE) and hillsides (HI). These two evergreen species were typical culturally representative species not only due to their ornamental, stress-tolerance properties, but also because they symbolized the eternal spirit of the deceased [63]. The dominant species of government/community/institutional ground (GC) was *Sophora japonica* Linn, which usually provides a place for residents to relax and shade.




(**a**) (**b**)

**Figure 5.** The first two axes of the DCA ordination of environments and the composition of scattered large old tree species in Baoding City and Xiongan New Area. Districts and habitat types are presented as circles, and species as crosses. (**a**) DCA results for 23 districts and tree species; (**b**) DCA results for 7 habitats and tree species. Note: Please refer to Table S5 in the Supplementary Materials for the abbreviated species names. Abbreviated habitat categories: GC, government/community/institutional ground; RD, residential district; TE, temple; VF, village fringe; SRHS, scenic resort/historic site; HI, hillside; and CE, cemetery.

### *3.2. Socio-Cultural Valuation of the Scattered Large Old Trees by Local Residents and a Driving Factors Analysis*

#### 3.2.1. The Average WTP of Respondents for the Socio-Cultural Value of Scattered Large Old Trees

Among the 1114 questionnaires we issued, 1082 (97.13%) valid samples were collected, and 25 (2.31%) of the valid samples were counted as objectors, as they were unwilling to pay or could not pay for economic reasons. All the valid responses were included for a statistical analysis of the average WTP of respondents of different backgrounds (Table 4). The analysis showed that the mean WTP of males was significantly higher than that of females. The mean WTP of young and middle-aged (18~60 years old) respondents was much higher than others, and 49.82% of our respondents were over 60 years old. Regarding education levels, it seemed that respondents with a higher education level were more willing to pay for scattered large old trees' conservation, and the mean WTP of respondents with postgraduate degrees or higher even reached CNY 1112.00. The mean WTP of respondents that worked as corporate staff was the highest among occupations. But a majority of the respondents we encountered were farmers (67.47%), and their average WTP was CNY 84.30. Respondents with higher incomes generally had more WTP, except for the interval of 1000~1500, which was mainly caused by three particular cases that were willing to pay CNY 2000, 3000, and 5000, as we found. The average WTPs of respondents in the three investigated areas did not show a significant difference, but the mean WTP in Xiongan New Area was relatively lower than others, probably affected by ongoing large-scale reconstruction [64].

**Table 4.** Statistics of the average willingness to pay (WTP) of respondents for the socio-cultural value of scattered large old trees.

| Variables | Categories | Proportion of Respondents (%) | Average Willingness to Pay (WTP) (CNY /Person/Tree) | *p* Value of Significance Test of Group Difference | Divided WTPs for Different Connotations of the Socio-Cultural Value (CNY /Person/Tree) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Social Bond | Spiritual Attachment and Homesickness | Fengshui | Witnessing History | Creative Inspiration | Education |
| Gender | Male | 56.84 | 169.72 ± 30.58 | 0.022 * | 28.26 ± 4.39 | **51.80 ± 17.25** | 38.96 ± 0.36 | 25.27 ± 6.19 | 11.18 ± 1.74 | 13.98 ± 2.80 |
| | Female | 43.16 | 83.45 ± 15.92 | | 18.33 ± 4.31 | **21.00 ± 3.65** | 13.66 ± 0.09 | 15.61 ± 5.29 | 6.97 ± 1.63 | 8.23 ± 2.49 |
| Age | Under 18 years old | 2.03 | 61.86 ± 10.45 | 0.001 ** | 12.39 ± 4.20 | 10.10 ± 2.38 | 9.30 ± 2.62 | **15.51 ± 5.24** | 7.00 ± 2.20 | 7.58 ± 2.65 |
| | 18–40 years old | 13.68 | 255.05 ± 76.03 | | 43.83 ± 9.86 | **72.75 ± 22.88** | 42.36 ± 18.52 | 52.24 ± 19.27 | 19.91 ± 4.92 | 23.95 ± 7.25 |
| | 41–60 years old | 34.47 | 185.34 ± 42.08 | | 29.64 ± 6.53 | **61.03 ± 27.19** | 44.36 ± 12.82 | 25.59 ± 8.53 | 10.55 ± 2.01 | 13.77 ± 3.82 |
| | Over 60 years old | 49.82 | 65.13 ± 10.63 | | **15.06 ± 3.32** | 14.68 ± 1.71 | 13.58 ± 1.80 | 9.67 ± 2.74 | 5.74 ± 1.45 | 6.66 ± 1.95 |
| Education level | Primary school | 43.53 | 106.34 ± 26.70 | 0.000 *** | 18.82 ± 4.34 | **39.11 ± 21.32** | 18.85 ± 4.00 | 12.39 ± 3.44 | 7.95 ± 1.96 | 9.53 ± 3.22 |
| | Middle/high school | 48.71 | 113.03 ± 21.03 | | 22.85 ± 4.28 | 25.77 ± 3.33 | **28.77 ± 8.49** | 18.42 ± 5.89 | 7.62 ± 1.07 | 9.33 ± 1.75 |
| | Bachelor's degree | 7.30 | 356.09 ± 128.36 | | 50.11 ± 13.20 | **101.31 ± 38.78** | 78.32 ± 35.34 | 65.38 ± 26.23 | 29.34 ± 9.20 | 31.62 ± 11.98 |
| | Postgraduate degree or higher | 0.46 | 1112.00 ± 974.42 | | 214.68 ± 196.58 | 331.98 ± 292.69 | 22.98 ± 14.00 | **424.48 ± 394.25** | 10.40 ± 7.50 | 107.48 ± 98.16 |
| Occupation | Student | 3.60 | 67.46 ± 9.13 | 0.000 *** | 15.04 ± 3.34 | **18.25 ± 3.51** | 6.54 ± 1.44 | 15.91 ± 4.21 | 5.15 ± 1.28 | 6.58 ± 2.05 |
| | Corporate staff | 2.77 | 554.80 ± 329.31 | | 87.99 ± 30.85 | **152.16 ± 98.75** | 124.04 ± 89.87 | 102.28 ± 66.30 | 37.38 ± 21.10 | 50.95 ± 30.22 |
| | Civil servant/institutional officer | 2.87 | 359.03 ± 161.45 | | 64.59 ± 34.16 | **111.75 ± 50.08** | 35.52 ± 16.49 | 91.43 ± 64.11 | 20.91 ± 5.87 | 34.84 ± 16.41 |
| | Self-employed | 6.65 | 121.81 ± 24.75 | | 20.17 ± 6.49 | **32.32 ± 7.65** | 13.20 ± 3.11 | 29.37 ± 7.23 | 13.95 ± 4.24 | 13.36 ± 3.95 |
| | Retiree | 3.51 | 99.21 ± 35.68 | | 20.09 ± 7.03 | **28.63 ± 13.21** | 16.97 ± 10.53 | 24.37 ± 11.43 | 5.42 ± 1.71 | 3.73 ± 1.10 |
| | Unemployed | 7.30 | 75.41 ± 20.44 | | 16.91 ± 5.88 | 16.63 ± 4.00 | **18.96 ± 7.50** | 7.74 ± 2.57 | 10.25 ± 4.12 | 4.92 ± 2.04 |
| | Farmer | 67.47 | 84.30 ± 10.07 | | 16.51 ± 1.96 | 20.25 ± 2.26 | **23.15 ± 3.73** | 9.58 ± 1.49 | 6.29 ± 1.02 | 8.46 ± 1.96 |
| | Other | 5.82 | 522.25 ± 232.60 | | 80.97 ± 40.60 | **212.90 ± 158.86** | 83.69 ± 63.38 | 89.81 ± 51.75 | 24.62 ± 11.26 | 30.27 ± 16.06 |
| Personal monthly fixed income | 0–200 | 28.84 | 45.94 ± 4.75 | 0.000 *** | 11.06 ± 1.52 | **11.07 ± 1.20** | 10.98 ± 1.88 | 5.36 ± 0.83 | 4.83 ± 1.28 | 3.84 ± 0.61 |
| | 200–500 | 17.38 | 56.67 ± 9.11 | | 11.26 ± 2.22 | 14.75 ± 2.51 | **16.92 ± 3.65** | 5.17 ± 0.86 | 3.98 ± 1.16 | 4.58 ± 0.93 |
| | 500–1000 | 16.45 | 80.56 ± 15.08 | | **18.94 ± 3.34** | 17.43 ± 3.40 | 16.86 ± 5.75 | 8.23 ± 1.93 | 6.32 ± 1.69 | 13.29 ± 4.80 |
| | 1000–1500 | 6.65 | 241.44 ± 85.24 | | 46.34 ± 16.82 | 55.23 ± 17.68 | **80.38 ± 30.85** | 23.25 ± 11.10 | 15.71 ± 7.26 | 19.97 ± 15.27 |
| | 1500–2000 | 6.10 | 80.58 ± 18.59 | | 14.12 ± 3.03 | **17.68 ± 4.23** | 10.56 ± 3.05 | 13.81 ± 5.01 | 10.47 ± 3.50 | 6.82 ± 2.28 |
| | 2000–3000 | 10.63 | 187.23 ± 47.68 | | 38.62 ± 14.83 | **40.50 ± 6.93** | 32.40 ± 8.10 | 36.24 ± 12.50 | 19.05 ± 6.50 | 20.44 ± 9.03 |
| | 3000–5000 | 8.04 | 217.41 ± 61.35 | | 41.11 ± 12.85 | 56.17 ± 18.49 | 21.39 ± 5.76 | **58.17 ± 23.78** | 15.07 ± 3.88 | 25.51 ± 6.92 |
| | ≥5000 | 5.91 | 638.59 ± 263.04 | | 73.59 ± 33.96 | **275.74 ± 162.02** | 135.32 ± 74.72 | 107.91 ± 55.81 | 22.32 ± 9.92 | 24.33 ± 14.11 |
| Place of residence | Laiyuan County | 71.44 | 142.27 ± 25.15 | 0.604 | 26.28 ± 4.06 | **40.10 ± 13.71** | 32.70 ± 7.17 | 20.08 ± 5.20 | 9.93 ± 1.62 | 13.17 ± 2.58 |
| | Urban core area of Baoding | 4.90 | 151.89 ± 93.76 | | 26.74 ± 18.81 | 43.78 ± 28.18 | 6.50 ± 1.66 | **53.65 ± 37.57** | 7.88 ± 1.50 | 13.34 ± 9.41 |
| | Xiongan New Area | 23.66 | 98.91 ± 11.14 | | 16.43 ± 2.80 | **32.61 ± 4.27** | 18.42 ± 3.43 | 17.42 ± 2.79 | 7.97 ± 1.54 | 6.06 ± 1.19 |
| Total | - | 100.00 | 132.48 ± 18.73 | | 23.97 ± 3.11 | **38.51 ± 9.94** | 28.04 ± 5.19 | 21.10 ± 4.19 | 9.36 ± 1.21 | 11.50 ± 1.92 |

t statistics with * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$. Mean ± standard error. The top-valued socio-cultural connotation was emphasized in bold.

As revealed in Table 4, the overall mean WTP for the socio-cultural value of scattered large old trees in the study area was CNY 132.48 per year per person. The divisions of WTP following six types of socio-cultural value connotations were ranked as follows: spiritual attachment and homesickness (38.51) > fengshui (28.04) > social bonds (23.97) > witnessing history (21.01) > education (11.5) > creative inspiration (9.36). Respondents over 60 years old attached more importance to the "social bond" connotation that was closely related to their casual activities of shading and gathering under the trees. In addition, though "spiritual attachment and homesickness" was appreciated by most of the respondents, farmers valued "fengshui" most in their perceptions.

#### 3.2.2. Factors Determining Local Residents' WTP for the Socio-Cultural Value of Scattered Large Old Trees

As displayed in Table 5, factors determining local residents' WTP for the socio-cultural value of scattered large old trees were consistent based on the results of Model 1 (ordered logit) and Model 2 (ordered probit). Gender, age, and personal monthly fixed income showed extremely significant correlations to WTP, which means that male, younger, and higher-income residents were willing to pay more. The other significant factors were education level, place of residence, DBH, and habitat; occupation, species, grade of tree age, tree height, and canopy size were insignificant factors. The model validity of model 3 (Random Forest) was not ideal, probably because of a high proportion of categorical variables in this study. The top-ranking factor of WTP was also personal monthly fixed income. But the second and third ranked factors of species and occupation were insignificant according to the other two models.

**Table 5.** Results of the three models of factors determining local residents' WTP for the socio-cultural value of scattered large old trees.

| | Explanatory Variables | Model 1: Ordered Logit | | Model 2: Ordered Probit | | Model 3: Random Forest | |
|---|---|---|---|---|---|---|---|
| | | Coefficient | Standard Error | Coefficient | Standard Error | IncNodePurity | Importance Ranking |
| Demographic characteristics | Gender | −0.450 *** | 0.117 | −0.282 *** | 0.067 | 0.014 | 10 |
| | Age | −0.565 *** | 0.086 | −0.322 *** | 0.049 | 0.031 | 9 |
| | Education level | 0.282 ** | 0.102 | 0.149 * | 0.059 | 0.107 | 5 |
| | Occupation | 0.027 | 0.040 | 0.015 | 0.023 | 0.132 | 3 |
| | Personal monthly fixed income | 0.192 *** | 0.028 | 0.110 *** | 0.016 | 0.200 | 1 |
| | Place of residence | 0.199 * | 0.081 | 0.109 * | 0.047 | 0.014 | 11 |
| Characteristics of scattered large old trees | Species | −0.009 | 0.015 | −0.007 | 0.008 | 0.152 | 2 |
| | Grade of tree age | 0.192 | 0.101 | 0.099 | 0.058 | 0.009 | 12 |
| | Tree height | −0.020 | 0.014 | −0.013 | 0.008 | 0.064 | 8 |
| | DBH | 0.002 * | 0.001 | 0.001 * | 0.000 | 0.109 | 4 |
| | Canopy size | −0.001 | 0.016 | 0.001 | 0.009 | 0.088 | 6 |
| | Habitat | −0.107 ** | 0.038 | −0.057 ** | 0.022 | 0.080 | 7 |
| Model validation | | Log likelihood: −1549.63<br>Pseudo $R^2$: 0.0670<br>Prob > chi2: 0.000 | | Log likelihood: −1550.84<br>Pseudo $R^2$: 0.0663<br>Prob > chi2: 0.000 | | % Var explained: 5.08 | |

t statistics with * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

### *3.3. Socio-Cultural Value Mapping of Scattered Large Old Trees at Different Scales*

As illustrated in Figure 6a, the village-level population was mainly concentrated in the southeast of the study area. Some 7.88% of the villages and 42.39% of the towns possessed scattered large old trees, and most of them were in the northwest area (Figure 6b,c). The average annual gross socio-cultural values of scattered large old trees were CNY 0.77 million on the village scale and CNY 2.24 million on the township scale. On the county/district scale, the annual gross socio-cultural value of scattered large old trees was highest in Yi County (CNY 93.59 million), with Western Qing Tombs that harbor a high density of large old trees, and lowest in Anxin County (CNY 0.10 million), where most of the Baiyandian

Lake is located. The annual gross socio-cultural value of scattered large old trees in the whole study area amounted to CNY 349 million. For a single scattered large old tree, the average annual socio-cultural value was CNY 169,500.

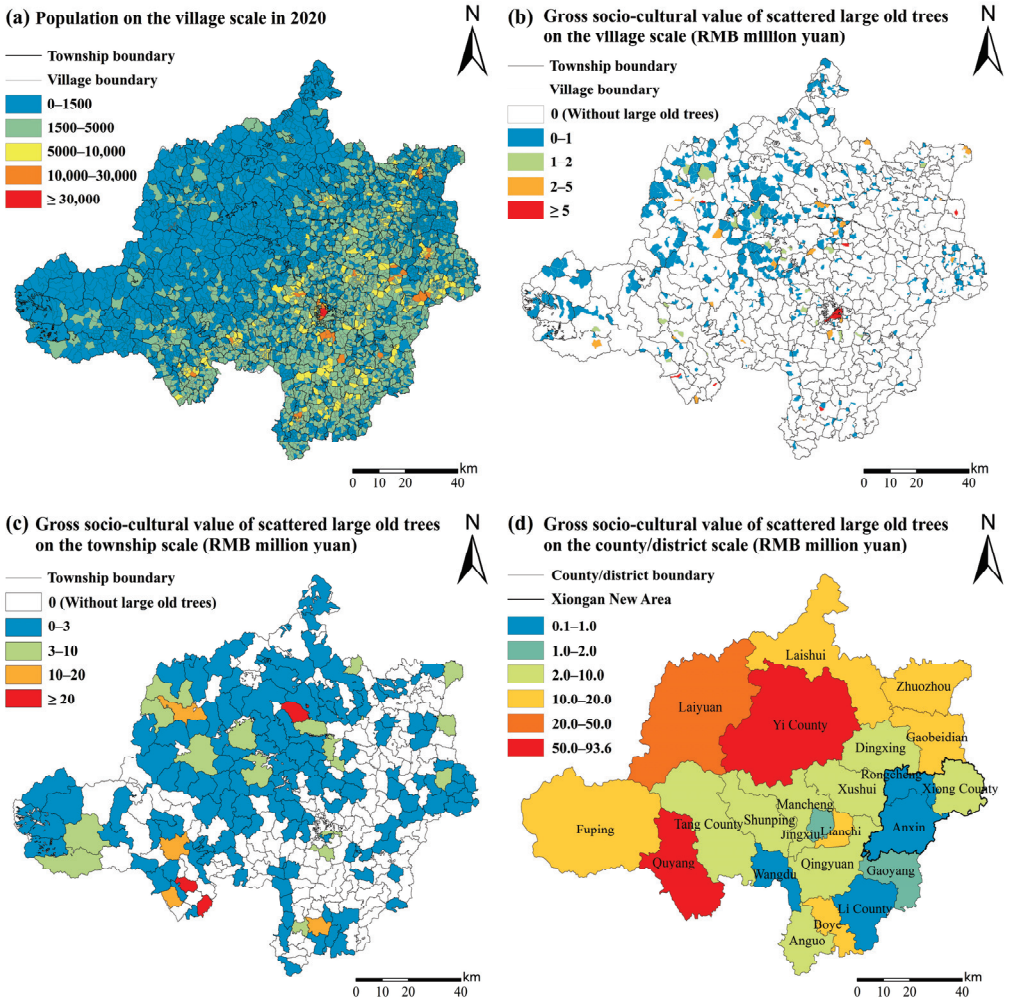



**Figure 6.** Estimation of gross socio-cultural value of scattered large old trees in Baoding City and Xiongan New Area. (**a**) Population distribution on the village scale in 2020; (**b**) value distribution on the village scale; (**c**) value distribution on the township scale; (**d**) value distribution on the county/district scale.

## 4. Discussion

### *4.1. Rural Large Old Tree Protection Is Faced with More Challenges*

Our study revealed that the large old trees in Baoding City and Xiongan New Area were generally at a relatively younger stage, with normal growth performance but poor living environments, in accordance with the results reported in Hebei Province in China [65]. Some 96.99% of the trees resided in the countryside, and the tree density was 0.10 trees/km$^2$, which is very close to the nationwide statistical result of 95.15% and 0.13 trees/km$^2$, respectively [7,37]. Similar to previous studies [14,20,66], the distribution of scattered large old trees showed an agglomerative pattern, with several clusters in Yi County, Laiyuan, and Quyang. A greater tree number was found in habitats of village fringe (VF), government/community/institutional ground (GC), and scenic resort/historic site (SRHS). The top-ranking habitat of village fringe (VF) was in accordance with the results of a study conducted in Jiangsu Province that showed villages and farmland accommodated more heritage trees [41]. But in the mega-cities of Beijing [21] and Macau [15], studies revealed that parks and gardens accommodated the most large old trees. The difference may be

due to a discrepancy of driving forces in urban and rural areas concerning the long-term persistence of large old trees.

Higher levels of species diversity in large old trees enhance resistance to environmental changes [67]. The adjusted species richness of our study area was 5.22, relatively lower than that in Beijing City (7.42) [21], Luoyang City (10.07) [14], and Jiangsu Province (18.56) [41]. This may be partly due to an absence of data on clustered large old trees in this study, but could also imply a diversity loss in rural large old trees. The top-ranking species were all indigenous, with strong physiological resistance to local environmental stress (such as drought and frost), or could bear edible fruits enjoyed by local residents. This finding confirmed the former perspective that species' biological traits and human utilization attributes drive the long-term persistence of old trees [12,68]. The species distribution varied considerably among the 23 districts/counties and had an obvious gradient differentiation from the mountain to plain areas, and plain areas had fewer species. This phenomenon was consistent with the conclusion generated by Li et al. [41] that elevation range shift was the strongest explanatory variable for the species diversity variation of heritage trees. More tree numbers and species appeared in the habitats of village fringe (VF) and government/community/institutional ground (GC) in this study, and government/community/institutional ground (GC) had the most unique tree species. This result was different from former findings in Jiangsu Province [41] and Hong Kong [69] that parks and gardens had the most unique species. Compared with parks and gardens, the habitats of village fringe (VF) and government/community/institutional ground (GC) are more diversely distributed and inconvenient for management, so large old tree protection in rural areas faces more difficulties than in urban areas.

### *4.2. Socio-Cultural Valuation of Rural Large Old Trees and Driving Factors*

The ratio of unwillingness to pay (un-WTP) for the socio-cultural value of scattered large old trees was only 2.31% in this study, which was relatively low compared with former studies that revealed that 55.6% were unwilling to pay for urban heritage tree conservation in Guangzhou [30], 27.36% were unwilling to pay in Taiwan [31]) and 44.1% were unwilling to pay for urban green space conservation in Beijing [70]). The hidden causes of this may be that the above three studies were all conducted in urban areas. The reported reasons for urban objectors mainly include the desired responsibility of the municipal government for management, and distrust of authorities' performance. But in rural areas, where scattered large old trees are usually collectively owned by the village, it seems that their socio-cultural connections with local residents are closer, and the willingness for autonomous management of large old trees is stronger for rural residents. Thus, most of the respondents in this study showed a positive attitude toward the contingent socio-cultural valuation.

We also showed that the mean WTP of males was significantly higher than that of females in this study, which is different from former research that found the WTP of male respondents for protection of an urban iconic tree was significantly lower than that of females [59]. The mean WTP of young and middle-aged (18~60 years old) respondents was much higher than others, which is similar to the findings of Lin et al. [31]. But 67.47% of the respondents we encountered were farmers, and 59.3% of the farmers were aged over 60, which is a typical reflection of rural population aging in China [71]. The mean WTP of our respondents was CNY 132.48, and CNY 84.30 for the farmer group; the two figures were all relatively higher in comparison to previous studies that reported mean WTPs of CNY 24.67 per year per household for conserving heritage trees of common tree species in Guangzhou [30], CNY 55.96 per year per person for a 1000-year-old tree in Taichung [31], and CNY 40.06 per year per person for urban green space conservation in Beijing [70]. According to our survey, 73.6% of the farmers' personal monthly fixed income was below 1000 CNY, much lower than that of the urban residents. Therefore, this study showed the stronger individual willingness of rural residents (especially farmers) to pay for large old tree conservation.

A previous study by Hartel et al. [72] used network analysis to understand farmers' value perception of large old trees, and found that socio-cultural values such as identity and history were most highly valued. The results of our study provide further understanding of the way rural residents rank different connotations, which was as follows: spiritual attachment and homesickness > fengshui > social bond > witnessing history > education > creative inspiration. Hartel et al. [72] also discovered that the "shade" value for large old trees is only indicated by older farmers, and this study found that respondents over 60 years old attached more importance to the "social bond" connotation that was closely related to shading. Moreover, farmers attached more importance to "fengshui" in their value perceptions.

The driving factors analysis showed that demographic characteristics influence WTP more than the community characteristics of large old trees. Both the ordered logit and probit models showed that gender, age, and personal monthly fixed income were significantly correlated to WTP. Male, younger, and higher-income residents were willing to pay more. A few former studies have also reported similar results considering the factors of age and income, but the influence of gender was biased [30,59,73]. Among the factors of large old tree community characteristics, only DBH and habitat were correlated with the WTP, which means that the socio-cultural value of bigger trees and those growing in certain habitats is more appreciated by rural residents.

This study, for the first time, gave a multi-scale assessment and geographic mapping of the gross socio-cultural value of rural scattered large old trees. According to our assessment, the average annual socio-cultural value for a single scattered large old tree was CNY 169,500, while Yang [74] evaluated the historical and cultural value of an 800-year-old tree in Beijing and found a result of CNY 3.04 million. The disparity may be due to the discrepancy in the economic background of the respondents, as well as the difference in the number of people that the large old trees were related to. The annual gross socio-cultural value of scattered large old trees within the whole study area amounted to CNY 349 million. According to a news report on the issue of the Beijing local standard, "Specification for the Routine Maintenance and Management of Ancient and Famous Woody Plants" [75], the annual budget for the management and protection of ancient and famous trees of Tier 1 and Tier 2 was CNY 1400 and 900, respectively (http://www.agronet.com.cn/tech/442972.html (accessed on 15 December 2023)). It can be estimated that the total annual budget for the protection of the large old trees is about CNY 1 million, which is far below the gross socio-cultural value they provide. Therefore, the protection situation of large old trees can be much improved if their socio-cultural value is fully recognized and utilized by the public.

### *4.3. Implications for Rural Large Old Trees' Protection with Multi-Scale Strategies*

Though experiencing rapid urbanization during the recent decades, the Chinese government has made great efforts to conserve large old tree resources. Actions such as forest law revision by adding articles on large old tree conservation, conducting national-level ancient and famous tree investigations, and issuing technical regulations for the management and conservation of old and notable trees, etc., have been taken. However, the protection situation is still unbalanced, as a number of large old trees, especially those in rural areas, still lack management, and local governments are faced with excessive pressures under the conventional government-dominant model. Based on the results of this study, we proposed a conceptual framework by integrating spatial analysis and contingent valuation for a socio-cultural value assessment and the multi-scale protection of large old trees (Figure 7), which consists of five steps, as follows.

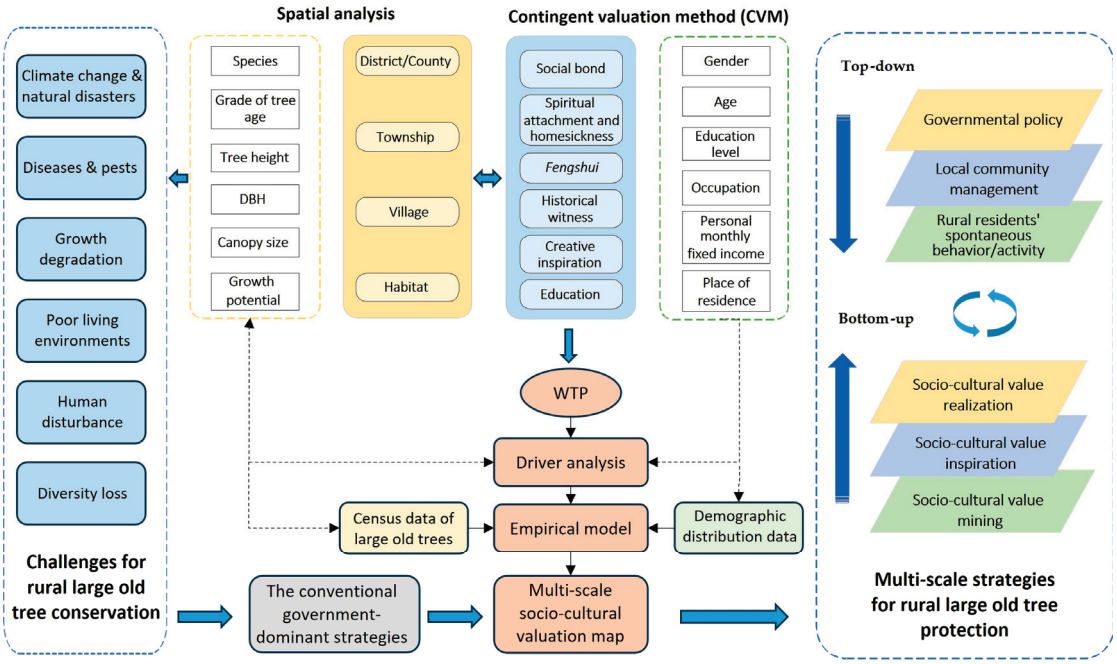



**Figure 7.** A conceptual framework for the integrated socio-cultural value assessment and multi-scale protection of large old trees.

Firstly, statistical and spatial analyses of local large old tree resources should be conducted based on census data. This will provide a full understanding of the protection situation and potential challenges of the trees. For example, in this study, the distribution clusters of Yi County, Laiyuan, and Quyang, and the most-accommodated habitats of village fringe (VF) and government/community/institutional ground (GC) were identified, challenges of diversity loss and poor living environments were uncovered.

Secondly, perceptions of the socio-cultural value of large old trees by local residents can be generated using CVM, based on which a comparative analysis of the mean WTP for the socio-cultural and divided connotations among groups can be conducted.

Thirdly, demographic characteristics and large old tree community indicators that have influence on the WTP can be analyzed by selecting key variables and constructing empirical models [76]. As in this study, the key variables were gender, age, personal monthly fixed income, education level, DBH, and tree habitat.

Fourthly, local data of the key variables should be generated and put into the empirical model for a further simulation of WTP in unsurveyed areas. In this case study, however, we omitted this step and used the mean WTP of Laiyuan County as a substitute because of a deficiency of village-level demographic data. This problem can be solved with governmental support in other cases. After this step, a socio-cultural value map of large old trees can be generated at different scales of county level, township level, village level, and individuals.

Lastly, based on the above analysis and socio-cultural valuation map, multi-scale rural large old tree protection strategies can be proposed. From a top-down perspective, the hotspot areas (e.g., Yi County, Laiyuan, and Quyang in this case study) can be assisted by issuing official titles of heritage tree cultural benchmarks. Local communities should pay more attention to key habitat protection and management areas that harbor the most trees and species; for rural residents, strategies such as tree adoption can be implemented to support residents' spontaneous willingness to pay for tree conservation. From a bottom-up perspective, we suggest incorporating the socio-cultural value of large old trees into the indicator system of GEP accounting, as issued by the National Development and Reform Commission and National Bureau of Statistics in China [77]. This non-use value, if properly circulated as a typical exploration of GEP value realization, will be profitable

not only for tree conservation, but also for the national strategy of rural revitalization. In addition, the socio-cultural value should be strengthened according to the importance ranking of different connotations. For example, this study found that spiritual attachment and homesickness was the most recognized value type, but the values of education and creative inspiration appeared to be neglected. Therefore, on one hand, the highly valued spiritual attachment to large old trees should be used rationally, following the case of Central Himalaya [27]; on the other hand, strategies can be made to enrich biocultural diversity as it relates to large old trees, e.g., by setting up popular science centers in relation to ancient trees for children and young people, constructing ancient tree art creation parks, and expanding culturally valuable output by organizing short video competitions, etc. The optimized conservation strategies can be updated at a five- or ten-years interval, starting from the first step following the conceptual framework [78].

## 5. Conclusions

Governments are faced with the unique challenge of fulfilling large-scale targeted protection within the context of the global decline in large old tree populations. However, the human value of large old trees is often neglected in this conservation [22]. In this study, we conducted an integrated study of the spatial distribution and contingent valuation of scattered large old trees in Baoding City and Xiongan New Area, intending to support a multi-scale conservation strategy; the main conclusions are as follows:

(1) The scattered large old trees in the study were generally at a relatively younger stage, with normal growth performance, but poor living environments. Some 96.99% of the trees resided in the countryside, and the tree density was 0.10 trees/km$^2$, which is similar to the situation reported in former studies focused on a larger provincial and national scope. The distribution of scattered large old trees showed an agglomerative pattern, with several clusters in Yi County, Laiyuan, and Quyang, and a greater tree number was found in the habitats of village fringe (VF), government/community/institutional ground (GC), and scenic resort/historic sites (SRHS).

(2) The adjusted species richness of scattered large old trees in the study area was 5.22, which is relatively lower than that in urban places, which may imply a loss of diversity in rural large old trees. The species distribution varied considerably among the 23 districts/counties, and had an obvious gradient differentiation from the mountain to plain areas, and plain areas had fewer species. The habitats of village fringe (VF) and government/community/institutional ground (GC) had the most unique tree species, which was different from the urban findings that parks and gardens had the highest diversity of large old trees.

(3) The ratio of unwillingness to pay (un-WTP) for the socio-cultural value of scattered large old trees was relatively low compared with former studies in urban areas. The overall average WTP for the socio-cultural value of scattered large old trees in this study was CNY 132.48 per year per person, and CNY 84.30 per year per person for the farmer group. The amount was much higher than similar studies conducted in larger cities, which indicated the closer spiritual connection of rural residents to large old trees. The influence of demographic characteristics was stronger than that of community characteristics on the WTP for large old trees' socio-cultural value. Economic income was the most significant factor determining residents' WTP. In addition, gender, age, education level, place of residence, DBH, and tree habitat were also factors that significantly influenced WTP. This study provides further understanding of the ranking of six socio-cultural value connotations, in terms of importance, by rural residents: spiritual attachment and homesickness > fengshui > social bond > witnessing history > education > creative inspiration.

(4) This study, for the first time, conducted a multi-scale assessment and geographic mapping of the gross socio-cultural value of rural scattered large old trees. The annual gross socio-cultural value of scattered large old trees in the study area was estimated to be CNY 349 million, CNY 0.77 million on the village scale, and CNY 2.24 million on the township scale on average. For a single scattered large old tree, the average annual

socio-cultural value amounted to CNY 169,500. Based on the case study, a conceptual framework integrating spatial analysis and contingent valuation for a socio-cultural value assessment and the multi-scale protection of large old trees was proposed. Following the five main steps, a socio-cultural value map of large old trees can be generated at different scales, and conventional government-dominated large old tree protection can be improved by promoting strategies of top-down multilevel participation and bottom-up socio-cultural value recognition. Further research is required, however, on aspects of empirical model utilization and economic/political routes to value recognition.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15010018/s1, Table S1. Content of the questionnaire survey; Table S2. Description and coding of independent variables; Table S3. Genera ranking of scattered large old trees in Baoding City and Xiongan New Area; Table S4. Species ranking of scattered large old trees in Baoding City and Xiongan New Area; Table S5. Abbreviated species names of scattered large old trees in Baoding City and Xiongan New Area; Figure S1. Distribution of the sampled scattered large old trees for socio-cultural value investigation; Data sharing of the census data of scattered large old trees in Baoding City and Xiongan New Area.

**Author Contributions:** N.Y.: Conceptualization, Data curation, Investigation, Formal analysis, Writing—original draft, Writing—review and editing. C.G.: Data curation, Investigation, Formal analysis, Writing—original draft. J.Q.: Conceptualization, Validation, Writing—review and editing. S.S.: Conceptualization, Funding acquisition, Validation. B.N.: Conceptualization, Investigation. H.W.: Conceptualization, Funding acquisition, Validation, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Natural Science Foundation of Hebei Province (Grant No. number D2022201004); the Science and Technology Plan Project of Hebei Province (Grant No. 225A4802D); the Scientific Research Project for the Ecological Product Value Realization Mechanism Pilot Construction in Baoding City (Grant No. 13060022P00JR2610037W); the Advanced Talents Incubation Program of Hebei University (Grant No. 521100223217); and the Collaborative Innovation Center for Baiyangdian Basin Ecological Protection and Beijing–Tianjin–Hebei Sustainable Development.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to a third party (the Baoding Natural Resources and Municipal Planning Bureau (Forestry Bureau)) data ownership.

**Acknowledgments:** We would like to thank the Baoding Natural Resources and Municipal Planning Bureau (Forestry Bureau) for providing open access census data of large old trees.

**Conflicts of Interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

1. Cannon, C.H.; Piovesan, G.; Munné-Bosch, S. Old and ancient trees are life history lottery winners and vital evolutionary resources for long-term adaptive capacity. *Nat. Plants* **2022**, *8*, 136–145. [CrossRef] [PubMed]
2. Gilhen-Baker, M.; Roviello, V.; Beresford-Kroeger, D.; Roviello, G.N. Old growth forests and large old trees as critical or-ganisms connecting ecosystems and human health. A review. *Environ. Chem. Lett.* **2022**, *20*, 1529–1538. [CrossRef] [PubMed]
3. Jones, G.M.; Keane, J.J.; Gutiérrez, R.J.; Peery, M.Z. Declining old-forest species as a legacy of large trees lost. *Divers. Distrib.* **2018**, *24*, 341–351. [CrossRef]
4. Piovesan, G.; Cannon, C.H.; Liu, J.; Munné-Bosch, S. Ancient trees: Irreplaceable conservation resource for ecosystem restoration. *Trends Ecol. Evol.* **2022**, *37*, 1025–1028. [CrossRef] [PubMed]
5. Lindenmayer, D.B.; Laurance, W.F.; Franklin, J.F. Global Decline in Large Old Trees. *Science* **2012**, *338*, 1305–1306. [CrossRef] [PubMed]
6. Lindenmayer, D.B. Conserving large old trees as small natural features. *Biol. Conserv.* **2017**, *211*, 51–59. [CrossRef]
7. Liu, J.; Lindenmayer, D.B.; Yang, W.; Ren, Y.; Campbell, M.J.; Wu, C.; Luo, Y.; Zhong, L.; Yu, M. Diversity and density patterns of large old trees in China. *Sci. Total Environ.* **2019**, *655*, 255–262. [CrossRef]
8. Zhang, X.; Wang, L.; Liu, Z.; Zheng, T.; Cao, Y.; Liu, X. The current situation and countermeasures for conservation of ancient and famous trees in Laoshan, Qingdao, China. *Ciência Rural* **2019**, *49*, 1–13. [CrossRef]

9. Lindenmayer, D.B.; Laurance, W.F. The Unique Challenges of Conserving Large Old Trees. *Trends Ecol. Evol.* **2016**, *31*, 416–418. [CrossRef]
10. Lindenmayer, D.B.; Laurance, W.F. The ecology, distribution, conservation and management of large old trees. *Biol. Rev.* **2017**, *92*, 1434–1458. [CrossRef]
11. Lu, Z.; Zhu, L.; Lu, J.; Shen, N.; Wang, L.; Liu, S.; Wang, Q.; Yu, W.; Kato-Noguchi, H.; Li, W.; et al. Rejuvenation in-creases leaf biomass and flavonoid accumulation in Ginkgo biloba. *Hortic. Res.* **2022**, *9*, uhab018. [CrossRef] [PubMed]
12. Liu, J.; Xia, S.; Zeng, D.; Liu, C.; Li, Y.; Yang, W.; Yang, B.; Zhang, J.; Slik, F.; Lindenmayer, D.B. Age and spatial distribution of the world's oldest trees. *Conserv. Biol.* **2022**, *36*, e13907. [CrossRef] [PubMed]
13. Huang, L.; Jin, C.; Zhen, M.; Zhou, L.; Qian, S.; Jim, C.Y.; Lin, D.; Zhao, L.; Minor, J.; Coggins, C.; et al. Biogeographic and anthropogenic factors shaping the distribution and species assemblage of heritage trees in China. *Urban For. Urban. Green.* **2020**, *50*, 126652. [CrossRef]
14. Hou, H.; Zhang, L.; Bi, H.; He, J.; Cai, E.; Ren, W. Differential characteristics and driving forces of the spatial distribution of heritage trees in Luoyang, an ancient capital of China. *Front. Environ. Sci.* **2022**, *10*, 993333. [CrossRef]
15. Zhang, H.; Lai, P.Y.; Jim, C.Y. Species diversity and spatial pattern of old and precious trees in Macau. *Landsc. Urban. Plan.* **2017**, *162*, 56–67. [CrossRef]
16. Yin, L. Resources Investigation and Characteristic Analysis of Ancient and Famous Trees in Meiling National Forest Park, Jiangxi Province. Master's Thesis, Jiangxi Agricultural University, Nanchang, China, 2019; p. 73. (In Chinese)
17. Huang, L.; Tian, L.; Zhou, L.; Jin, C.; Qian, S.; Jim, C.Y.; Lin, D.; Zhao, L.; Minor, J.; Coggins, C.; et al. Local cultural beliefs and practices promote conservation of large old trees in an ethnic minority region in southwestern China. *Urban For. Urban. Green.* **2020**, *49*, 126584. [CrossRef]
18. Lijuan, T. The Composition and Characteristics of Heritage Trees in Ethnic Minority Areas in Southwest China: A Case Study of Guizhou Wuchuan Gelao and Miao Ethnic Autonomous County. Master's Thesis, Chongqing University, Chongqing, China, 2018. (In Chinese)
19. Orłowski, G.; Nowak, L. The importance of marginal habitats for the conservation of old trees in agricultural landscapes. *Landsc. Urban. Plan.* **2007**, *79*, 77–83. [CrossRef]
20. Qiu, Z.; Hu, X.; Qian, H.; Wei, B.; Liao, K. Analysis of spatial distribution characteristics of ancient and famous trees in Xintian County. *J. Cent. South Univ. For. Technol.* **2022**, *42*, 1–11. (In Chinese)
21. Fu, Q.; Qiu, E.; Zhang, Y.; Huang, L.; Wang, H.; Jiang, S. Discussion of the Distribution Pattern and Driving Factors of Large Old Tree Resources in Beijing. *Forests* **2022**, *13*, 1500. [CrossRef]
22. Blicharska, M.; Mikusinski, G. Old Trees: Cultural Value. *Science* **2013**, *339*, 904. [CrossRef]
23. Blicharska, M.; Mikusiński, G. Incorporating Social and Cultural Significance of Large Old Trees in Conservation Policy. *Conserv. Biol.* **2014**, *28*, 1558–1567. [CrossRef] [PubMed]
24. Breyne, J.; Dufrêne, M.; Maréchal, K. How integrating 'socio-cultural values' into ecosystem services evaluations can give meaning to value indicators. *Ecosyst. Serv.* **2021**, *49*, 101278. [CrossRef]
25. Reid, W.V.; Mooney, H.A.; Cropper, A.; Capistrano, D.; Carpenter, S.R.; Chopra, K.; Dasgupta, P.; Dietz, T.; Duraiappah, A.K.; Hassan, R. *Ecosystems and Human Well-Being-Synthesis: A Report of the Millennium Ecosystem Assessment*; Island Press: Washington, DC, USA, 2005.
26. Chen, J.; Lin, W.; Zhang, Y.; Dai, Y.; Chen, B. Village Fengshui Forests as Forms of Cultural and Ecological Heritage: Interpretations and Conservation Policy Implications from Southern China. *Forests* **2020**, *11*, 1286. [CrossRef]
27. Subrat Sharma, H.C.R.L. Conservation of Natural Resources Through Religion: A Case Study from Central Himalaya. *Soc. Nat. Resour.* **1999**, *12*, 599–612. [CrossRef]
28. Venkatachalam, L. The contingent valuation method: A review. *Environ. Impact Assess. Rev.* **2004**, *24*, 89–124. [CrossRef]
29. Vo, N.X.; Huyen Nguyen, T.T.; Van Nguyen, P.; Tran, Q.V.; Vo, T.Q. Using contingent valuation method to estimate adults' willingness to pay for a future coronavirus 2019 vaccination. *Value Health Reg. Issues* **2021**, *24*, 240–246. [CrossRef] [PubMed]
30. Chen, W.Y. Public willingness-to-pay for conserving urban heritage trees in Guangzhou, south China. *Urban For. Urban. Green.* **2015**, *14*, 796–805. [CrossRef]
31. Lin, H.; Chuang, Y.; Liu, W. Assessing the economic value of an iconic urban heritage tree. *Forest Policy Econ.* **2020**, *118*, 102216. [CrossRef]
32. Son, H.; Xia, T.; Kim, Y.; Kang, T. A Value Evaluation Research of the Old-growth and Giant Tree—Focus on Gyeongju Gyerim's Zelkova Serrata. *J. Korean Inst. Tradit. Landsc. Archit.* **2016**, *34*, 51–56. [CrossRef]
33. Wang, B.; Xiu, X.; Lan, S. Monetary Valuation of the Cultural Value of Ancient and Famous Trees. *Issues For. Econ.* **2016**, *36*, 565–570. (In Chinese)
34. Wang, J.; Yu, F.; Ma, G.; Peng, F.; Zhou, X.; Wu, C.; Yang, W.; Wang, C.; Cao, D.; Jiang, H.; et al. Gross economic-ecological product as an integrated measure for ecological service and economic products. *Resour. Conserv. Recycl.* **2021**, *171*, 105566. [CrossRef]
35. Yang, H.; Gou, X.; Ma, W.; Xue, B. Research and application of GEP: China' s experience in natural capital accounting. *Front. Environ. Sci.* **2023**, *11*, 75. [CrossRef]
36. Hartel, T.; Réti, K.; Craioveanu, C. Valuing scattered trees from wood-pastures by farmers in a traditional rural region of Eastern Europe. *Agric. Ecosyst. Environ.* **2017**, *236*, 304–311. [CrossRef]

37. Yamin, Z. The results of the second national survey of ancient and famous tree resources were announced. *Land. Green.* **2022**, *9*, 16–17. (In Chinese)
38. Baoding Bureau Of Statistics. *Baoding Economy Statistical Yearbook*; China Statistics Press: Beijing, China, 2020.
39. Wu, J. The Supernova Remnant of More than 4100 Years Ago Was Discovered—Emperor Yao's Jingxing (PKS 1209-52). *Chin. Astron. Astrophys.* **2023**, *47*, 309–334.
40. Lu, P.; Li, M.; Fu, S.; Henrietta Onyebuchi, C.; Zhang, Z. Modeling the warring states period: History dynamics of initial unified empire in China (475 BC to 221 BC). *Expert Syst. Appl.* **2023**, *230*, 120560. [CrossRef]
41. Li, K.; Zhang, G. Species Diversity and Distribution Pattern of Heritage Trees in the Rapidly-Urbanizing Province of Jiangsu, China. *Forests* **2021**, *12*, 1543. [CrossRef]
42. Yang, J.; Huang, X. The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. *Earth Syst. Sci. Data* **2021**, *13*, 3907–3925. [CrossRef]
43. Zhu, H.; Li, Y.; Liu, Z.; Fu, B. Estimating the population distribution in a county area in China based on impervious surfaces. *Photogramm. Eng. Remote Sens.* **2015**, *81*, 155–163. [CrossRef]
44. Chen, B.; Coggins, C.; Minor, J.; Zhang, Y. Fengshui forests and village landscapes in China: Geographic extent, socioecological significance, and conservation prospects. *Urban For. Urban. Green.* **2018**, *31*, 79–92. [CrossRef]
45. Wang, X.; Fan, B.; Li, Z.; Song, J.; Liu, S.; Chen, L.; Cai, D.; Yin, G.; Jiang, Z. Forest cultural value evaluation index system and methodology. *Acta Ecol. Sin.* **2021**, *41*, 202–212. (In Chinese)
46. Wan, C.; Shen, G.Q.; Choi, S. Underlying relationships between public urban green spaces and social cohesion: A systematic literature review. *City Cult. Soc.* **2021**, *24*, 100383. [CrossRef]
47. Zhao, P.; Ren, Z. Distribution and cultural value of old tree resources in Xinzhou city. *J. Arid. Land. Resour. Environ.* **2023**, *37*, 150–156. (In Chinese)
48. Hartl, C.; St. George, S.; Konter, O.; Harr, L.; Scholz, D.; Kirchhefer, A.; Esper, J. Warfare dendrochronology: Trees witness the deployment of the German battleship Tirpitz in Norway. *Anthropocene* **2019**, *27*, 100212. [CrossRef]
49. Senetra, A. Forests as an important spatial element in elaboration of the esthetic value maps for rural landscapes. *Sylwan* **2015**, *159*, 757–766.
50. Qian, H. Large-scale biogeographic patterns of vascular plant richness in North America: An analysis at the generic level. *J. Biogeogr.* **1998**, *25*, 829–836. [CrossRef]
51. Simon, J.S. Density Estimation. *Stat. Sci.* **2004**, *19*, 588–597.
52. Guo, L.; Cheng, S.; Liu, J.; Wang, Y.; Cai, Y.; Hong, X. Does social perception data express the spatio-temporal pattern of perceived urban noise? A case study based on 3,137 noise complaints in Fuzhou, China. *Appl. Acoust.* **2022**, *201*, 109129.
53. Wang, Z.; Smyth, R. A hybrid method for creating Lorenz curves. *Econ. Lett.* **2015**, *133*, 59–63. [CrossRef]
54. Yang, Y.; Bao, G.; Zhang, D.; Zhai, C. Spatial Distribution and Driving Factors of Old and Notable Trees in a Fast-Developing City, Northeast China. *Sustainability* **2022**, *14*, 7937. [CrossRef]
55. Lai, P.Y.; Jim, C.Y.; Da Tang, G.; Hong, W.J.; Zhang, H. Spatial differentiation of heritage trees in the rapidly-urbanizing city of Shenzhen, China. *Landsc. Urban. Plan.* **2019**, *181*, 148–156. [CrossRef]
56. Grilli, L.; Rampichini, C. Ordered Logit Model. In *Encyclopedia of Quality of Life and Well-Being Research*; Maggino F, Ed.; Springer International Publishing: Cham, Switzerland, 2020; pp. 1–4.
57. Bellizzi, M.G.; Eboli, L.; Forciniti, C.; Mazzulla, G. Air Transport Passengers' Satisfaction: An Ordered Logit Model. *Transp. Res. Procedia* **2018**, *33*, 147–154. [CrossRef]
58. Piedra-Bonilla, E.B.; Da Cunha, D.A.; Braga, M.J. Climate variability and crop diversification in Brazil: An ordered probit analysis. *J. Clean. Prod.* **2020**, *256*, 120252. [CrossRef]
59. Liu, W.; Chuang, Y. To exclude or not to exclude? The effect of protest responses on the economic value of an iconic urban heritage tree. *Urban. For. Urban. Green.* **2022**, *71*, 127551. [CrossRef]
60. Levantesi, S.; Piscopo, G. The Importance of Economic Variables on London Real Estate Market: A Random Forest Approach. *Risks* **2020**, *8*, 112. [CrossRef]
61. Rhodes, J.S.; Cutler, A.; Moon, K.R. Geometry- and Accuracy-Preserving Random Forest Proximities. *IEEE Trans. Pattern Anal. Mach. Intell.* **2023**, *45*, 10947–10959. [CrossRef] [PubMed]
62. Nachouki, M.; Mohamed, E.A.; Mehdi, R.; Abou Naaj, M. Student course grade prediction using the random forest algorithm: Analysis of predictors' importance. *Trends Neurosci. Educ.* **2023**, *33*, 100214. [CrossRef] [PubMed]
63. Wang, B. Study on Cultural Value of the Ancient and Famous Tree in China. Master's Thesis, Nanjing Agricultural University, Nanjing, China, 2009; p. 94. (In Chinese)
64. Wang, Q.; Zhou, X.; Huo, Z.; Shi, L.; Zhang, Y. Building an Up-and-Coming City-An overview of the Geological Data Sharing Service Platform of the Xiongan New Area. *China Geol.* **2019**, *3*, 566–568. [CrossRef]
65. Lu, H. Characteristics of the ancient and famous tree resources in Hebei Province and conservation strategies. *Hebei For.* **2012**, *7*, 20–21. (In Chinese)
66. Jianhua, X.; Cheng, L.; Congcong, L.; Ying, T.; Danmiao, Z. Study on the Resource Characteristics and Spatial Distribution of Ancient and Famous Trees: Taking the Tonglu County of Zhejiang Province as an Example. *Nat. Prot. Areas* **2022**, *2*, 110–118. (In Chinese)

67. Bourne, K.S.; Conway, T.M. The influence of land use type and municipal context on urban tree species diversity. *Urban. Ecosyst.* **2014**, *17*, 329–348. [CrossRef]
68. Huang, L.; Jin, C.; Pan, Y.; Zhou, L.; Hu, S.; Guo, Y.; Meng, Y.; Song, K.; Pang, M.; Li, H.; et al. Human activities and species biological traits drive the long-term persistence of old trees in human-dominated landscapes. *Nat. Plants* **2023**, *9*, 898–907. [CrossRef] [PubMed]
69. Jim, C.Y.; Zhang, H. Species diversity and spatial differentiation of old-valuable trees in urban Hong Kong. *Urban. For. Urban. Green.* **2013**, *12*, 171–182. [CrossRef]
70. Xu, F.; Wang, Y.; Xiang, N.; Tian, J.; Chen, L. Uncovering the willingness-to-pay for urban green space conservation: A survey of the capital area in China. *Resour. Conserv. Recycl.* **2020**, *162*, 105053. [CrossRef]
71. Houkai, W.; Peng, Y.; Shukun, W. *China Rural Revitalization Survey (2021)*; China Social Sciences Press: Beijing, China, 2022.
72. Hartel, T.; Nita, A.; Rozylowicz, L. Understanding human-nature connections through value networks: The case of ancient wood-pastures of Central Romania. *Sustain. Sci.* **2020**, *15*, 1357–1367. [CrossRef]
73. Majumdar, S.; Deng, J.; Zhang, Y.; Pierskalla, C. Using contingent valuation to estimate the willingness of tourists to pay for urban forests: A study in Savannah, Georgia. *Urban For. Urban. Green.* **2011**, *10*, 275–280. [CrossRef]
74. Yu, Y.; Minghua, T.; Guowei, Q.; Zhenyu, Z.; Chunhui, L. Monetization evaluation on the comprehensive value of old and valuable trees in cities—A case study of "Marguis of Shade" in Beijing. *J. Arid. Land. Resour. Environ.* **2019**, *33*, 185–191. (In Chinese)
75. *DB11/T 767-2010*; Specification for Routine Maintenance and Management of Ancient & Famous Woody Plants. Quality and Technical Supervision Bureau: Beijing, China, 2011.
76. Li, S.; Chen, Z.; Guo, L.; Hu, F.; Huang, Y.; Wu, D.; Wu, Z.; Hong, X. How Do Spatial Forms Influence Psychophysical Drivers in a Campus City Community Life Circle? *Sustainability* **2023**, *15*, 10014. [CrossRef]
77. The National Bureau of Development and Reform; the National Bureau of Statistics. *Standard for the Gross Ecological Product Value Accounting*; People's Publishing House: Beijing, China, 2022.
78. Hong, X.; Cheng, S.; Liu, J.; Guo, L.; Dang, E.; Wang, J.; Cheng, Y. How Should Soundscape Optimization from Perceived Soundscape Elements in Urban Forests by the Riverside Be Performed? *Land* **2023**, *12*, 1929. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# Integrated Assessment and Restoration Pathways for Holistic Ecosystem Health in Anxi County, China

**Tianyuan Zhu [1], Shuming Zhang [2], Yubo Wang [3], Cuiping Wang [4] and Haowei Wang [1,5,*]**

[1] Key Laboratory of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China; zhuzhuzhuty@163.com
[2] Anxi Natural Resources Administration, Quanzhou 362400, China; 23232440@163.com
[3] School of Big Data and Software Engineering, Chongqing University, Chongqing 400044, China; wyblalala@gmail.com
[4] College of Harbour and Coastal Engineering, Jimei University, Xiamen 361021, China; ping_autumn@163.com
[5] Xiamen Key Laboratory of Smart Management on the Urban Environment, Xiamen 361021, China
* Correspondence: hwwang@iue.ac.cn; Tel.: +86-592-619-0694

**Abstract:** Different types of ecosystems form a complex community of life. Hence, ecosystem protection and restoration should not focus solely on a single ecosystem. Ecosystem health assessments should consider the integrity and systematicity of interrelated ecosystems to inform rational environmental planning and management. In this study, the key characteristic indicators of major ecosystems (mountain, water, forest, and cropland) and ecosystem service capacity indicators in Anxi County, China, were selected to construct an integrated assessment system of ecosystem health that led to integrated ecosystem restoration pathways that addressed the county's ecological problems. The results revealed that ecosystem health was higher in the western and lower in the eastern parts of the county. Throughout the county, "medium" and "poor" ecosystem health levels predominated, revealing that overall ecosystem sustainability was weak. Ecosystem restoration programmes should be tailored to each health level. Where there was "excellent" and "good" ecosystem health ratings, those healthy ecosystem functions should be strengthened and maintained. In the "medium" health areas, the control and prevention of ecological problems should be strengthened. "Poor" health areas require immediate integrated ecological restoration projects that ensure the connectivity and coordination of restoration tasks in fragile ecosystems. This then will enhance holistic ecosystem stability and sustainability.

**Keywords:** ecosystem health; ecosystem community; ecological conservation and restoration; ecosystem services

**Citation:** Zhu, T.; Zhang, S.; Wang, Y.; Wang, C.; Wang, H. Integrated Assessment and Restoration Pathways for Holistic Ecosystem Health in Anxi County, China. *Sustainability* **2023**, *15*, 15932. https://doi.org/10.3390/su152215932

Academic Editor: Georgios Koubouris

Received: 27 September 2023
Revised: 9 November 2023
Accepted: 13 November 2023
Published: 14 November 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Ecosystems provide a substantial material base for human survival, and maintaining healthy ecosystems ensures the sustainability of human development [1]. There is no doubt that the industrialisation and urbanisation of human societies have developed rapidly by relying on natural resources and energy from ecosystems. However, the ecosystems have been stressed during this process and many have been altered and damaged by extensive human activities [2], thus exacerbating many ecological problems such as global warming, natural disasters, energy resource shortages, atmospheric pollution, and biodiversity reduction [3,4]. Due to massive human disturbances, Earth's ecosystem structure and function have changed dramatically, thus leading to a destabilisation of ecosystem functioning [5]. At the same time, when disturbances exceed an ecosystem's capacity for self-repair, that ecosystem can provide only lower-quality services, so social and economic benefits decline and the sustainable development of human well-being is limited [6–8]. Therefore, a key ecosystem research task is to better understand ecosystem health and

use that information to provide a strong scientific basis for environmental planning and management [9,10].

Healthy ecosystems maintain their integrity and stability while also providing ecological services to humans [11]. Ecosystem health research focuses on identifying ecological problems in specific ecosystem processes and ecological patterns, and on providing the basis for research methods that assess the degree of health or damage. This then provides a scientific basis for rational environment management, which also aids the sustainable development of ecology and human beings [12–14]. Ecosystem health has been explained from different perspectives (e.g., ecological and sociological). From an ecological perspective, ecosystem health is considered as a state of equilibrium achieved through the interactions among various biological populations within the ecosystem and their environment. From a sociological perspective, ecosystem health is viewed as a balance achieved when the ecosystem meets human well-being, and natural resources are utilized and protected in a reasonable manner. This perspective focuses more on the interrelationships between human society and the ecosystem. However, because different researchers may adopt distinct focuses and methodologies to define and assess ecosystem health, consequently, ecosystem health has yet to be defined in a coherent and clear manner [15–17].

The widely accepted concept of ecosystem health proposed by Costanza [1] pointed out that a healthy ecosystem can provide ecosystem services (ES) that support human society. The concept includes a "vigor-organisation-resilience" framework that combines ecosystem structure, function, and ESs to identify and analyse ecosystem health. In recent years, most ecosystem health studies have based their evaluation indicator systems on this framework [18–22]. To understand the functions and conditions of ecosystems, and to assess and address the vulnerability or degradation of ecosystems through effective, scientific methods, researchers have meticulously studied various types of ecosystems (e.g., marine ecosystems [23,24], river ecosystems [25,26], forest ecosystems [27,28], agroecosystems [29], wetland ecosystems [30,31], and desert ecosystems [32]). These studies have yielded important results that have provided strong scientific bases for ecosystem restoration. At the same time, in addition to basic research on ecosystem health, many countries, such as China, have instituted many ecological restoration projects [33]. To harmonise human society with the natural environment, restoration measures that promote the smooth operation of ecosystems help maintain and enhance the ability of those ecosystems to cope with environmental changes and human disturbances (e.g., vegetation restoration [34], desertification management [35], sandstorm management [36], water management [37], and soil and water conservation [38]). These ecological engineering projects have achieved significant positive results and have greatly improved ecological environments.

However, ecological conservation and restoration projects tend to focus on a single ecological element, and that severs the integrity of ecosystems and ignores the linkages in ecological processes. We must remember that the ecosystem is a large and complex community of life that interacts on multiple levels with the physical environment, and the subsystems within it are universally linked and interact with each other. One of the more common ecological problems in China is that population pressures and over-exploited resources have caused an expansion of arable land in mountainous areas, and that has led to problems such as degraded vegetation cover and reduced soil quality. These problems then exacerbate soil erosion problems, and multiple interactions among those problems creates a vicious cycle [39]. Additionally, while the stabilisation of a major ecosystem function can regulate the dynamic balance of a region's combined ecosystems, the degradation of a major ecosystem function can trigger a decline in the ES capacity of other ecosystems [40]. Therefore, how do we effectively explore overall ecosystem health and its integrated conservation and restoration? Obviously, the level of such holistic ecosystem health must be determined by constructing an integrated assessment model, and that is a key task in the process of exploring this issue.

Researchers have used various methods to conduct ecosystem assessment studies at different scales (e.g., fuzzy mathematical methods [41], grey system models [42], artificial

neural network models [43], and the composite index method [1]). However, from any perspective, research on integrated diagnosis and assessment of ecosystem health is particularly scarce [44]. In addition, considering ecosystem restoration pathways from a holistic perspective, sorting out ecological problems that exist in different ecosystems may be an effective way to promote the preservation or restoration of ecosystem health and create a beneficent cycle.

Based on the interconnectedness of ecosystem types, the main objective of this study is to construct an integrated assessment system that combines key characteristic indicators of the major ecosystem types and of the ES capacity indicators. The final assessment results can reflect the integrated ecosystem health and provide services for the integrated ecological restoration in Anxi County. The study area used to test the assessment system was Anxi County, Fujian Province, China. Finally, we developed integrated ecosystem restoration pathways based on the county's ecological issues. The implementation of restoration pathways can be guided by the integrated assessment results to develop integrated restoration plans for different regions. This study provides a scientific basis for ecosystem health regulation and ecological restoration in municipalities in Anxi County.

## 2. Study Area

### *2.1. Anxi County Conditions*

Anxi County (24°50′–25°26′ N, 117°35′–118°17′ E) is in the southeastern Fujian Province in China and has an area of 3057.28 km$^2$ (Figure 1). It is in the central and southern subtropical maritime monsoon climate zone and has abundant sunshine (1850 h per year), sufficient rainfall (1500–2000 mm), and an average annual temperature of 16.0–21.0 °C. Its geomorphological types are complicated and diverse, and the terrain differs greatly between the east and west parts of the county. Also, a dense network of rivers and abundant water resources include the Jinjiang River basin water system in the eastern part of the county and the Jiulongjiang River basin in the western part. Together, they account for 64.8% and 35.2% of the county's river basin area, respectively. The southern part of the county is subtropical rainforest and the middle is subtropical evergreen broad-leaved forest.

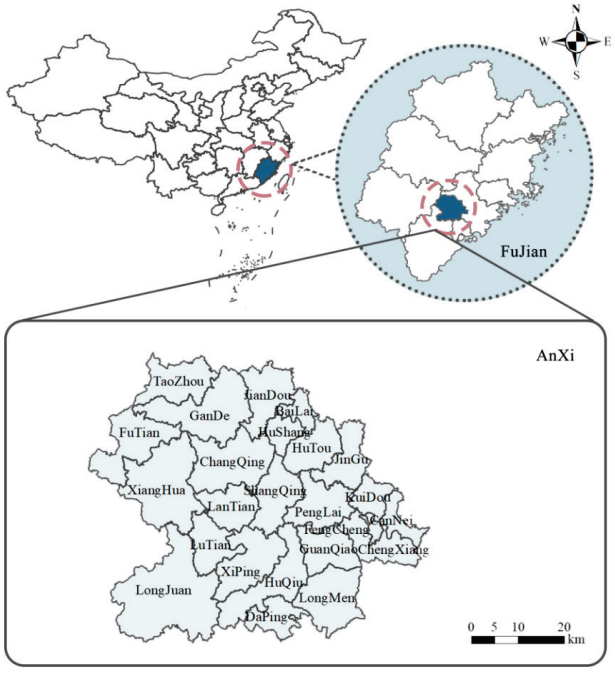



**Figure 1.** The location of Anxi County in Fujian Province, China. Smaller subdivisions within the county are townships.

### *2.2. Ecosystem Issues*

Anxi County's rapid social and economic development has placed it among the top 100 counties in China in terms of comprehensive strength. However, many ecological problems have emerged due to the impact of urban development and construction. In recent years, the local government has intensified the protection of the ecological environment and developed a series of relevant policies to vigorously support the implementation of ecosystem conservation and restoration work. To determine Anxi County's current ecological problems, we examined field research and pertinent information provided by the Anxi Natural Resources Administration.

Anxi County is composed of mountain, water, forest, and cropland ecosystems. The main problems in the mountain ecosystem are exposed hill pits, destroyed mountain surfaces and vegetation, a high incidence of geological disasters from mining, and an accumulation of loose surface sediments. The water ecosystem suffers from accumulated pollutants in the rivers, inadequate sewage disposal facilities, reduced water system connectivity, and untreated sewage discharge. Meanwhile, the forest ecosystem suffers fragmentation, a monocultural stand structure, disastrous pest outbreaks, and a reduction in natural forests. Finally, the main cropland ecosystem problems are low soil fertility, an irrational fertilisation structure, a low rate of cropland reclamation, and contaminated soil.

The interactions among these ecological problems have intensified water and soil losses and created fragile shelterbelt forests, severe water pollution loads, and degraded cropland. Ultimately, the results of those interactions further contribute to a reduced ES capacity and overall ecosystem instability (Figure 2).

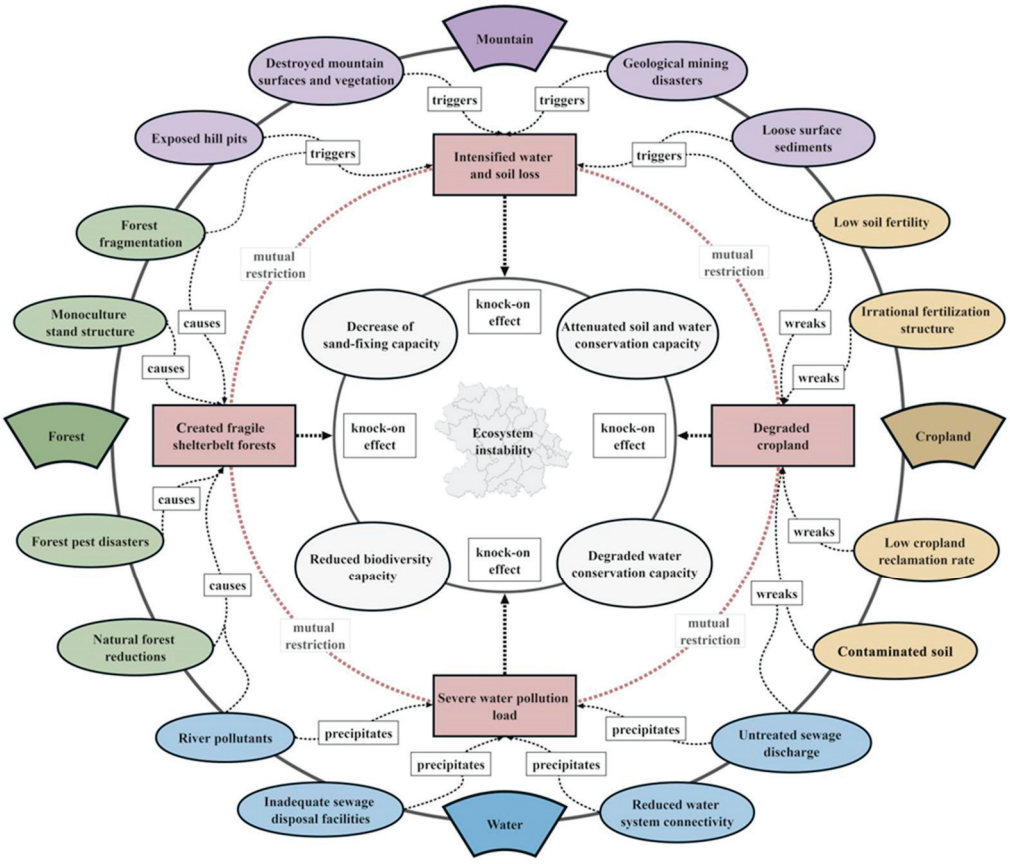



**Figure 2.** The relationships between the various ecological issues in Anxi County. Ecological issues in mountain, forest, water and cropland ecosystems (outer ring). These problems interact to create broader problems (next inner ring), which then contribute to reduced ecosystem service capacity and overall ecosystem instability (innermost ring).

## 3. Methodologies

### *3.1. Indicator System for Assessing Ecosystem Health*

#### 3.1.1. Establishing the Indicator System

To comprehensively assess ecosystem health, an evaluation indicator system must first be established. The indicators must be easily quantified and understood, as well as indicative of the topic being evaluated. From our study area, we have consulted a wealth of local planning documents and incorporated the insights of relevant experts. Finally, we selected key characteristic indicators of the major ecosystems and of the ES capacity to construct a comprehensive ecosystem health assessment system based on scientificity, comprehensiveness, and operability (Figure 3).

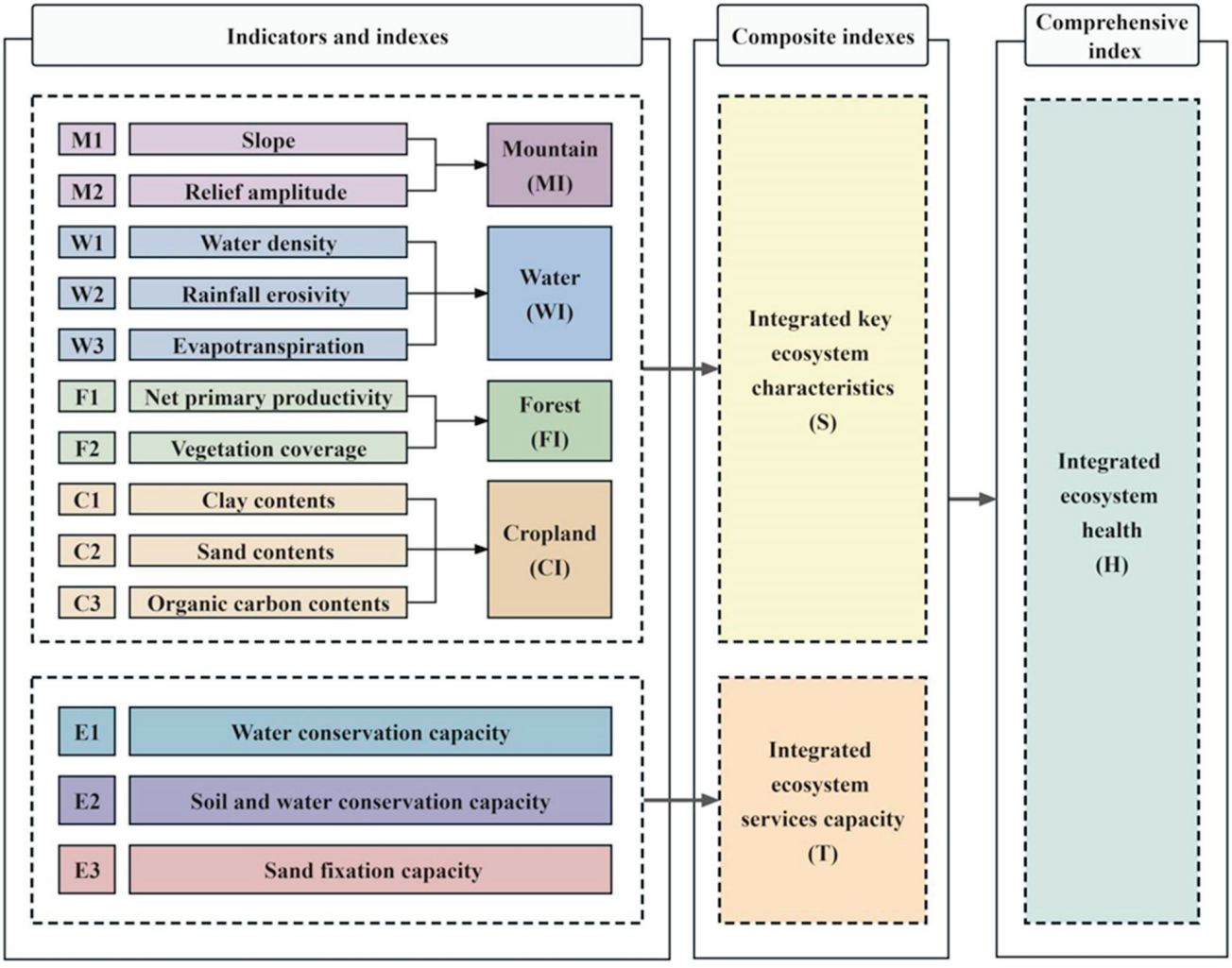



**Figure 3.** Comprehensive evaluation indicator system for ecosystem health in Anxi County. The indicators and indexes included the characteristic indicators for each of the four ecosystem types and their resulting composite indexes (top box) and the ecosystem service capacity indicators (bottom box). The composite indexes and comprehensive index show the progression of combining the indexes and indicators into a final assessment of the overall ecosystem health for the entire county.

#### Selection of the Key Characteristic Indicators for the Four Ecosystems

The study area is predominantly mountainous with many abandoned mines, and geological disasters such as landslides and collapses occur often. Therefore, we selected slope (M1) and relief amplitude (M2) as the two key characteristic indicators for the mountain ecosystem (Figure 3). Because M1 and M2 reflect the geomorphological pattern

and the steepness of the land surface, they best judge both the terrain complexity and the risk levels of natural disasters.

The study area has abundant water resources, but the water ecosystem's greatest problem is that the gradual disconnection between water systems is leading to limited ecological function. Therefore, the indicators selected for the water ecosystem were water density (W1), rainfall erosivity (W2), and evapotranspiration (W3). We selected W1 to reflect the overall distribution of water bodies, which enabled us to determine whether the region can maintain water cycle stability, as well as provide a strong water supply. Because the abundant rainfall and strong convective weather in the study area can cause heavy rainfall and flash floods, W2 was selected to reflect the potential impact of soil erosion caused by rainfall, and that then helps us judge whether the area is susceptible to rainfall erosion that could then cause serious soil erosion and natural disasters. The long and hot summers in parts of this area can cause rapid water evaporation from soil and vegetation. Therefore, W3 was selected to reflect the total amount of water vapour released by vegetation and the surface to the atmosphere, and that helped determine whether the soil can consistently provide enough water for vegetative growth.

The study area has abundant forest resources, but due to human activities, the natural forests are gradually giving way to planted, monoculture forests, thus resulting in low forest quality. Therefore, for the forest ecosystem, we selected net primary productivity (F1) and vegetation coverage (F2) as indicators. First, F1 was selected to reflect the energy remaining for other organisms in the ecosystem after the vegetation itself was consumed. This helps judge whether the ecosystem can then provide what those organisms need to survive and reproduce. Second, F2 indicates the level of forest resources and greening, which can then be used to judge the extent of vegetation resources coverage and the potential of those resources to help maintain ecosystem stability.

The study area is affected by both natural and anthropogenic factors such as steep terrain, frequent heavy rainfall, and irrational farming practices, and those factors have led to poor soil quality, as well as to a disaster-prone situation. Therefore, the indicators selected for the cropland ecosystem were soil quality indicators: clay (C1), sand (C2), and organic carbon (C3) contents. First, C1 reflects the soil water-retention property, and can be used to judge the soil's ability to retain water and nutrients. Next, C2 reflects the soil's water retention and wind erosion resistance properties and indicates the soil's susceptibility to nutrient loss and drought, as well as its ability to resist wind erosion. Finally, C3 reflects soil fertility and thus shows whether the soil can support crop growth and soil microorganisms.

Selection of the Ecosystem Service Capacity Indicators

The indicators selected for ES capacity were water conservation capacity (E1), soil and water conservation capacity (E2), and sand fixation capacity (E3) (Figure 3). Among these three indicators, E1 reflects the ecosystem's ability to intercept, infiltrate, store, and purify precipitation through its structure and interactivity with water. Thus, it was used to determine the ecosystem's ability to regulate the water cycle and the supply of water resources. Next, E2 reflects the ecosystem's ability, through the absorption and infiltration of rainfall combined with soil stabilisation by plant roots, to reduce soil fertility loss and to mitigate river silting. Thus, it was used to determine the ecosystem's ability to mitigate flooding, maintain the water table and water supply, prevent soil erosion, and improve soil quality. Finally, E3 reflects the ecosystem's ability to reduce soil bareness and weaken wind strength and sand carrying capacity by fixing soil and improving soil structure. Thus, it was used to determine the ecosystem's ability to resist soil erosion and wind-sand hazards. These ES capacity indicators were used to determine the study area's four ecosystems' abilities to maintain ecological function and security.

3.1.2. Data Sources

Data for this study were gathered as follows.

(1) Landsat-8 remote sensing image and Digital Elevation Model (DEM) data were acquired from the Geospatial Data Cloud Platform (https://www.gscloud.cn/ (accessed on 19 August 2022)). The remote sensing image data were collected in September 2019 with a resolution of 30 m. We used ENVI 5.3 (NV5 Geospatial, Hollywood, FL, USA) to pre-process the remote sensing image using cropping, fusion, radiometric calibration, and atmospheric correction. In addition, the 30 m resolution DEM data were used to extract land slope and relief amplitude in ArcGIS 10.5.
(2) Data on precipitation, evapotranspiration, wind speed, and net primary productivity with 500 m resolution for the years 2011–2020 were obtained from the National Earth System Science Data Centre, China (http://www.geodata.cn/ (accessed on 23 August 2022)).
(3) Soil data (clay, sand, and organic carbon contents) with 500 m resolution were obtained from the World Soil Database (https://www.fao.org/soils-portal/data-hub/ (accessed on 29 August 2022)).
(4) The Anxi Natural Resources Administration (http://www.fjax.gov.cn/ (accessed on 25 July 2022)) provided information that was used to determine the ecosystems' main problems, as well as data on water density.

Additonally, the indicators were resampled as raster data with a resolution of 250 m in ArcGIS 10.5. This choice was made in accordance with the detailed guidelines in China's "Guidelines for the Delineation of Ecological Conservation Redline" (https://www.mee.gov.cn/ (accessed on 12 September 2022)).

3.1.3. Indicator Calculations

The base data for the 13 indicators selected for this study were pre-processed and then spatially analysed in ArcGIS 10.5 (https://www.esri.com/ (accessed on 10 October 2022)). However, rainfall erosivity, vegetation coverage, and the ES capacity indicators required additional calculations as follows.

Vegetation Coverage and Rainfall Erosivity Calculations

We first calculated the normalized difference vegetation index (*NDVI*) extracted from the pre-processed Landsat-8 remotely sensed images and used that to calculate vegetation cover (*F*2) [45]:

$$NDVI = (Band4 - Band3)/(Band4 + Band3) \quad (1)$$

$$F2 = (NDVI - NDVI_{soil})/\left(NDVI_{veg} - NDVI_{soil}\right), \quad (2)$$

where *Band*3 is the infrared band, *Band*4 is the near-infrared band, $NDVI_{veg}$ is the information contributed by a fully vegetated surface, and $NDVI_{soil}$ is the information contributed by an unvegetated surface.

We used the formula in the "Guidelines for Measurement and Estimation of Soil Erosion in Production and Construction Projects" of China (http://www.swcc.org.cn/ (accessed on 12 September 2022)) to calculate rainfall erosivity (W2) based on 10 years of rainfall data for the study area. The formula is

$$R = 0.067P_d^{1.627}, \quad (3)$$

where $P_d$ is the average rainfall over the years.

Ecosystem Service Capacity Indicator Calculations

The ES capacity indicators (*E*1, *E*2, and *E*3) were calculated according to the functional ecosystem importance assessment methods in the "Guidelines for the Delineation

of Ecological Conservation Redline" in China (https://www.mee.gov.cn/ (accessed on 12 September 2022)). First, we calculated

$$E1 = NPP_{mean} \cdot F_{sic} \cdot F_{pre} \cdot (1 - F_{slo}), \quad (4)$$

where $NPP_{mean}$ is the average multi-year net primary productivity of vegetation, $F_{sic}$ is the soil percolation factor, $F_{pre}$ is the multi-year average precipitation factor, and $F_{slo}$ is the slope factor.

Before calculating $E2$, we first calculated the pre-amended soil erodibility factor ($K_{EPIC}$), and used it to calculate the amended soil erodibility factor ($K$):

$$K1 = 0.2 + 0.3exp[-0.0256m_{sand}(1 - m_{silt}/100)] \quad (5)$$

$$K2 = \left[m_{silt}/\left(m_{clay} + m_{silt}\right)\right]^{0.3} \quad (6)$$

$$K3 = 1 - 0.25orgC/[orgC + exp(3.72 - 2.95orgC)] \quad (7)$$

$$K4 = 1 - 0.7(1 - m_{sand}/100)/\{(1 - m_{sand}/100) + exp[-5.51 + 22.9(1 - m_{sand}/100)]\} \quad (8)$$

$$K_{EPIC} = K1 \cdot K2 \cdot K3 \cdot K4 \quad (9)$$

$$K = (-0.01383 + 0.51575K_{EPIC}) \cdot 0.1317, \quad (10)$$

where, $m_{sand}$, $m_{clay}$, $m_{silt}$, and $orgC$ are the sand, clay, silt, and organic carbon content of the soil, respectively.

Then,

$$E2 = NPP_{mean} \cdot (1 - K) \cdot (1 - F_{slo}). \quad (11)$$

Before calculating $E3$, we first calculated the multi-year average climatic erosive force ($F_q$) and the surface roughness factor ($D$) as follows:

$$F_q = \frac{1}{100}\sum_{l=1}^{12} u^3\left(\frac{ETP_i - P_i}{ETP_i}\right) \cdot d \quad (12)$$

$$D = 1/cos(\theta), \quad (13)$$

where $ETP_i$ is the monthly potential evapotranspiration, $P_i$ is the monthly precipitation, $d$ is the number of days in the month, and θ is the slope. Next,

$$E3 = NPP_{mean} \cdot K \cdot F_q \cdot D \quad (14)$$

### *3.2. Construction of a Comprehensive Index of Ecosystem Health*

#### 3.2.1. Entropy Weight Method

The entropy weight method is usually used to determine indicator weights in studies related to ecosystem health assessment [46,47]. This method objectively assigns weights that are used to judge the degree of dispersion of the indicator values, thus eliminating interference from subjective factors and avoiding the problem of overlapping information between multiple indicators. This then renders objective and reliable evaluation results [48]. In this study, this method was employed to calculate the weights of 10 characteristic indicators (M1, M2, W1, W2, W3, F1, F2, C1, C2, and C3) for the four ecosystem types in the study area.

Data Standardisation

Because of the large differences among the indicators' dimensions and quantities, their orders of magnitude must be eliminated to make the data easily and directly comparable. In the entropy weight method, indicators are classified as positive or negative. Specifically, a higher value of a positive indicator corresponds to a higher value of the comprehensive assessment, whereas a higher value of a negative indicator corresponds to a lower value of the comprehensive assessment. Therefore, they necessitate distinct calculation methods. The positive and negative indicators were standardised as follows, respectively:

$$X_{ij} = \frac{x_{ij} - Min(x_{ij})}{Max(x_{ij}) - Min(x_{ij})} \tag{15}$$

$$X_{ij} = \frac{Max(x_{ij}) - x_{ij}}{Max(x_{ij}) - Min(x_{ij})}, \tag{16}$$

where $X_{ij}$ is the standardised indicator value, $x_{ij}$ is the original indicator value, and $Min(x_{ij})$ and $Max(x_{ij})$ are the minimum and maximum indicator values, respectively.

Indicator Entropy Calculation

The indicator entropy calculation began with calculating $F_{ij}$, the integrated standardised value of the indicator, which was then used to calculate $J_j$, the entropy of the $j$th indicator:

$$F_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}} \tag{17}$$

$$J_j = -\frac{1}{\ln n} \sum_{j=1}^{n} F_{ij} \ln F_{ij}, \tag{18}$$

where $n$ is the number of evaluation indicators. If $F_{ij} = 0$, then $F_{ij} \ln F_{ij} = 0$.

Determination of Indicator Weights

Indicator weights were determined with

$$W_j = \frac{1 - J_j}{m - \sum_{j=1}^{m} J_j}, \tag{19}$$

where $W_j$ is the weight of the $j$th indicator and $m$ is the number of evaluation indicators.

3.2.2. Composite Index Determinations

The composite index method is used to determine the comprehensive level of a certain aspect in a complex system. It can transform indicators of different scales into a unified form [49]. We used this method to construct a composite index of each ecosystem's characteristic indicators and ES capacities (Figure 3).

First, using the entropy weight method (see Section 3.2.1), we determined the weights of each of the 10 characteristic indicators for the four ecosystems. Then, those weights were used to calculate the composite indexes of the key features of the mountain (*MI*), water (*WI*), forest (*FI*), and cropland (*CI*) ecosystems as follows:

$$MI = \sum_{j=1}^{m} W_j \cdot mi_j \tag{20}$$

$$WI = \sum_{j=1}^{m} W_j \cdot wi_j \tag{21}$$

$$FI = \sum_{j=1}^{m} W_j \cdot fi_j \tag{22}$$

$$CI = \sum_{j=1}^{m} W_j \cdot ci_j, \tag{23}$$

where $mi_j$, $wi_j$, $fi_j$, and $ci_j$ are the standardised values of the $j$th indicator of the mountain, water, forest, and cropland ecosystems, respectively.

Next, we considered each indicator to be equally important because the four ecosystems together form a single living community. Therefore, to integrate the key ecosystem characteristics' composite indexes ($S$) and ES capacities ($T$), each composite index or ES capacity indicator was given equal weight, as follows:

$$S = \frac{1}{4} \cdot MI + \frac{1}{4} \cdot WI + \frac{1}{4} \cdot FI + \frac{1}{4} \cdot CI \tag{24}$$

$$T = \frac{1}{3} \cdot E1 + \frac{1}{3} \cdot E2 + \frac{1}{3} \cdot E3. \tag{25}$$

#### 3.2.3. Integrated Ecosystem Health Assessment

While ESs may importantly inform the sustainability of ecosystems [50], ecosystem health valuation usually focuses on the ecosystem itself and ESs are often overlooked [51]. Healthy ecosystems not only maintain their stable structure, but also have the capacity to provide sustainable ESs to humans [44]. Therefore, linkages between ecosystems and ESs must be established [52,53]. While various ES research methods are gradually gaining attention, researchers are also adopting the relevant ES indicators as an important part of the indicator system [54]. Meanwhile, some researchers have developed a "vigor-organisation-resilience" framework that incorporates ES factors to more comprehensively assess ecosystem health [18]. Here, we assessed integrated ecosystem health based on integrated key ecosystem characteristics and integrated ES capacity as $H = ST$, where $H$ is the composite index of overall ecosystem health (Figure 3).

Finally, in ArcGIS 10.5, we classified each of the 13 indicators, and subsequently each of the integrated assessment indicators, into four grades based on the Jenks natural breaks classification method. This method is a statistical technique for dividing a continuous variable into categorical classes based on the inherent structure of the data. It involves identifying natural breaks, or inflection points in the data distribution, which serve as partition points to create classes that are relatively equal in size and represent distinct regions of the variable's range [55].

## 4. Results

### *4.1. Spatial Distributions of the Key Characteristic Indicators of the Four Ecosystems*

#### 4.1.1. Mountain Ecosystem

The study area's topography has much variation. In the central part, specifically Changqing, and the eastern part, which includes Hutou, Cannei, Fengcheng, Guanqiao, and Longmen, both slope (M1) and relief amplitude (M2) were comparatively low (Figure 4). However, the northwestern area, which includes Taozhou, Futian, and Gande, has considerably higher slope and greater relief amplitude, thus disasters, such as landslides and avalanches, occur frequently in those mountainous areas. Therefore, those areas have higher disaster risks and M1 and M2 are negative indicators. Also, the weights for M1 and M2 were 47.725% and 52.275%, respectively.

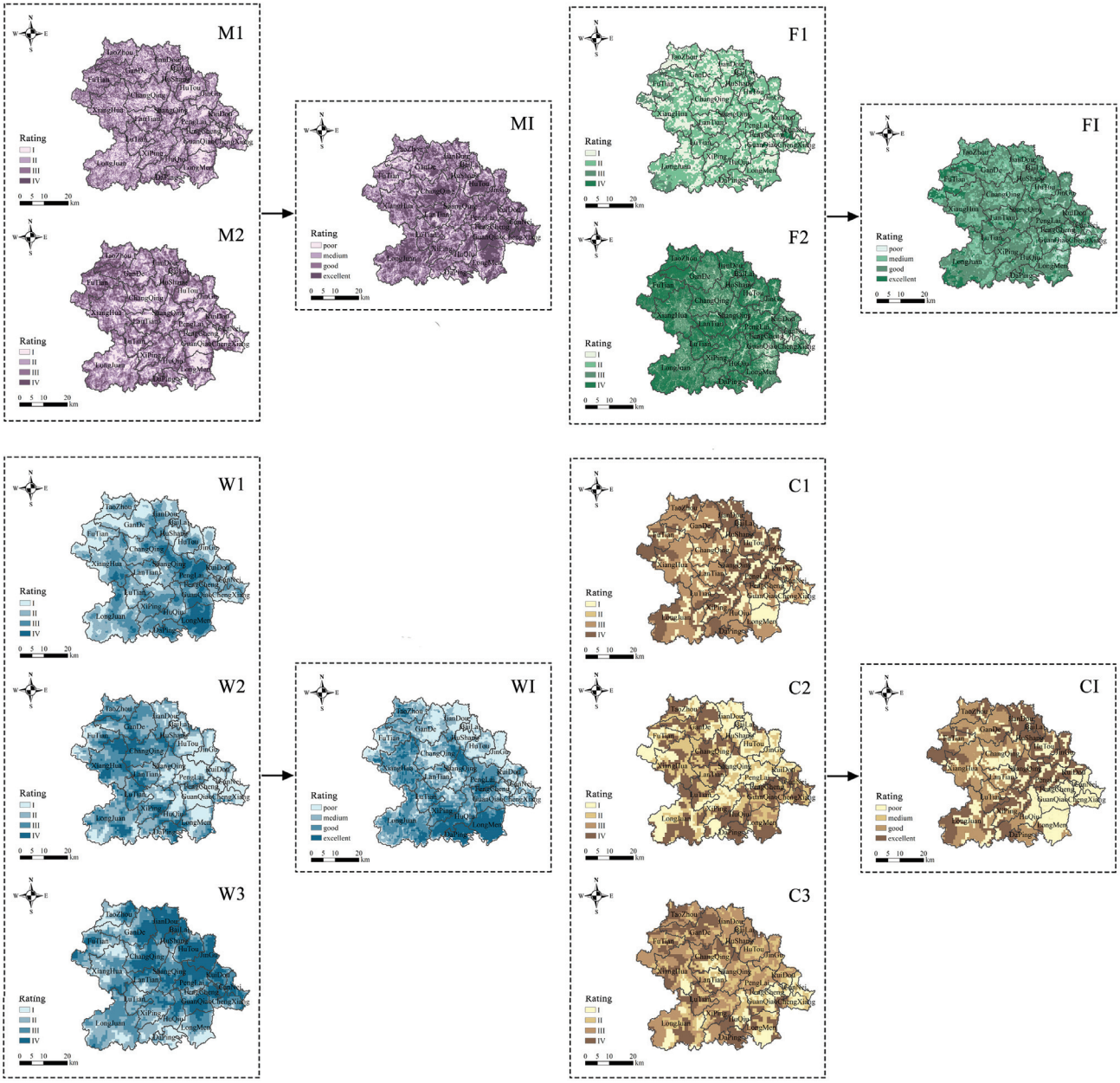



**Figure 4.** The spatial distributions of key characteristics of the four ecosystem types (purple, mountain; blue, water; green, forest; yellow, cropland) in Anxi County. Each ecosystem type's characteristic indicator spatial distribution maps are shown to the left of their composite index spatial distribution map. Higher grade numbers indicate higher values for each indicator. The composite characteristics maps rate the spatial distributions of each ecosystem's quality as poor, medium, good, or excellent. See Figure 3 for ecosystem type and indicator definitions.

In general, the mountain ecosystem is rated highly, but its composite index has no obvious spatial distribution pattern (Figure 4). Specifically, the central and eastern areas of the county (e.g., Changqing, Hutou, Guanqiao, and Longmen) have more "excellent" ratings than the other areas do. That part of the county has a gentle topography, so the frequency of natural disasters is relatively low. Areas rated "poor" are scattered throughout the study area, but there is a large area in Futian, Gande, and Taozhou. This type of area has a higher risk of safety hazards in the event of geological disasters such as landslides and mudslides.

4.1.2. Water Ecosystem

While W1 and W3 have similar spatial distribution characteristics, their higher grades were in Penglai, Guanqiao, Longmen, and Daping in the eastern part of the county (Figure 4). The grades were lower, especially for W1, in the northwest. Meanwhile, W2 had high grades in only small areas in Xianghua, Xiping, and Daping.

Because areas with high water density can provide more water ESs, W1 is a positive indicator. However, areas with high rainfall erosivity are prone to soil erosion, which causes potentially serious soil disturbance. Also, regions with high evapotranspiration can experience reduced local soil moisture that adversely impacts vegetation growth. Therefore, W2 and W3 are negative indicators. The entropy weighting method assigned W1, W2, and W3 weights of 39.369%, 14.424%, and 46.207%, respectively.

In general, the composite index for this ecosystem (WI) showed a general spatial distribution trend of higher ratings in the south and lower in the north. Specifically, the south is dominated by "excellent" and "good" ratings, and Huqiu, Daping, and Longmen have large "excellent" areas. Those townships' common characteristics are high water density, low rainfall erosivity, and low evapotranspiration. Poorly rated areas were in the central part (e.g., Gande and Changqing) and eastern edge of the county. This area is characterised by high evapotranspiration and low water density, which tends to reduce soil moisture content and accelerate groundwater depletion.

4.1.3. Forest Ecosystem

Anxi County has much vegetation cover (F2), with only small areas with little cover in Hutou, Fengcheng, Cannei, and Guanqiao in the east (Figure 4). Conversely, the county's overall net primary productivity (F1) was low, with a small number of high-value areas mainly in Fengcheng, Cannei, and Guanqiao. Areas with high net primary productivity have ample available energy for ecosystem members to use, and that contributes to the members' survival and reproduction. Also, areas with much vegetation cover are relatively rich in ESs. Therefore, both F1 and F2 are positive indicators and their weights were 57.309% and 42.691%, respectively.

In general, the forest composite index spatial distribution was moderate. Specifically, though, large areas in the west, including Gender, Futian, and Longjuan, had "excellent" ratings. This area is characterised by much vegetation coverage and net primary productivity that can provide high quality ESs to organisms. However, the eastern area, including Hutou, Guanqiao, Longmen, and a small part of Chengxiang were rated "poor". Although the net primary productivity of this area is high, the vegetation coverage is relatively low due to the large, urban population.

4.1.4. Cropland Ecosystem

Because soil with a low sand content (C2) had a high clay content (C1), and vice versa, the clay and sand spatial distributions trended oppositely, especially in the eastern part of the county (Figure 4). Meanwhile, soil organic carbon contents (C3) were generally high, with low value areas randomly distributed in the central and southern parts of the county.

Because soils with higher clay contents have stronger water-holding and fertility-holding properties than soils with less clay, areas with high-clay soils are less susceptible to drought. Also, high-organic-carbon-content soil promotes the growth and reproduction of soil microorganisms and provides more nutrients for crop growth. Thus, C1 and C3 are positive indicators. However, soil temperature fluctuates greatly in areas with high-sand-content soil. Such soil possesses weak water retention and fertility; thus, it is susceptible to drought. Therefore, C2 is a negative indicator. The weights for C1, C2, and C3 were 67.771%, 14.784%, and 17.445%, respectively.

In general, the spatial distribution of the cropland ecosystem composite index shows a "good-excellent-poor" distribution trend from west to east. The northeastern part of the county has large "excellent" areas, including Jiandou, Bailai, Hushang, Shangqing, Jingu,

and Penglai, which are characterised by soils with high clay and organic carbon contents and low sand contents. In contrast, the southeastern area (e.g., Longmen, Guanqiao, Chengxiang, Fengcheng, and Cannei) has large areas rated "poor", and they have soils with low clay and organic carbon contents and high sand contents. The fertility of the soil in that region is low and vulnerable to drought.

#### 4.1.5. The Spatial Distribution of Integrated Key Ecosystem Characteristics

In general, we found no distinct pattern in the spatial distribution of the integrated key ecosystem characteristics (Figure 5). Anxi County had large areas rated "medium", while the "excellent" rating applied to a small area, mainly in the centre of the county (e.g., Shangqing and Penglai) and in small parts of Longjuan, Lutian, Huqiu, and Longmen in the south. Also, areas with "poor" ratings were scattered throughout the county. Overall, most of the county was rated "poor" and "medium", thus indicating that the county's ecosystems possess a low ability to regenerate after sustaining damage.

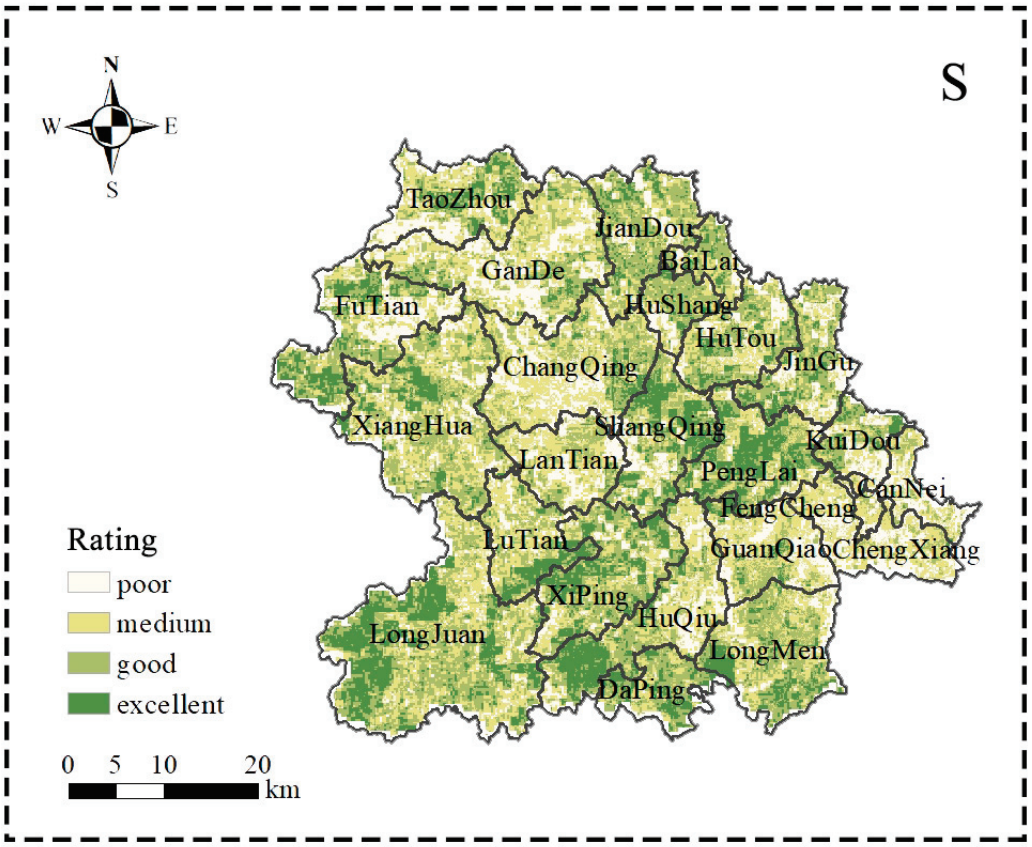



**Figure 5.** The spatial distribution of the integrated key ecosystem characteristics composite index (S in Figure 3) for Anxi County, China.

### *4.2. The Spatial Distributions of Ecosystem Service Capacity Indicators*

#### 4.2.1. Water Conservation Capacity

In general, E1′s spatial distribution trended higher in the west and lower in the east, but there was a small area rated "excellent" in Lantian (Figure 6). The areas with "good" and "medium" ratings were mainly distributed in the west, while the areas with "poor" ratings were mainly in the east. Overall, the county's ecosystems only weakly regulate regional water circulation and thus fall short at preventing floods and maintaining the quality of water sources, especially in the east.

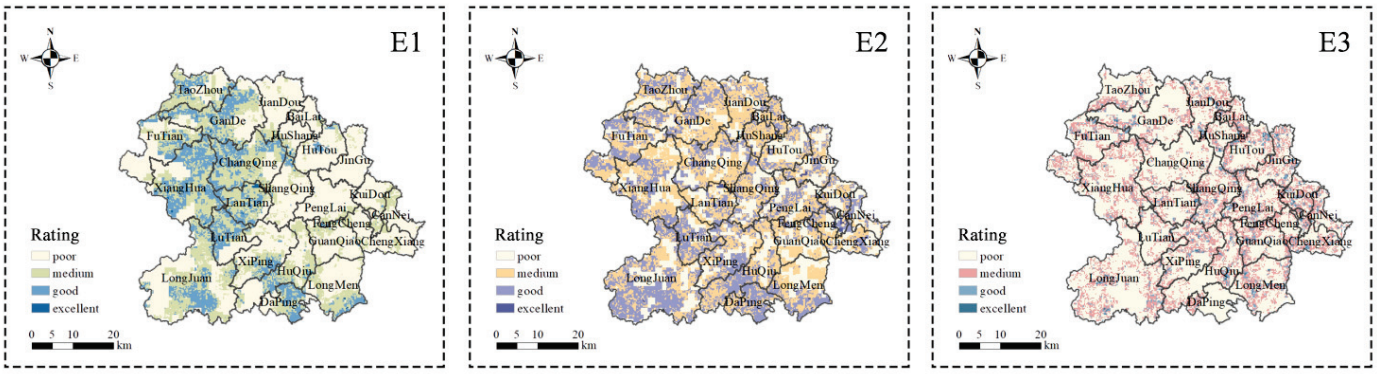



**Figure 6.** The spatial distributions of ecosystem service capacity indicators for Anxi County, China. (**E1**), water conservation capacity; (**E2**), soil and water conservation capacity; and (**E3**), sand fixation capacity.

#### 4.2.2. Soil and Water Conservation Capacity

In general, E2′s spatial distribution followed no distinct pattern, and "excellent" ratings were rare (Figure 6). However, areas with "good" and "medium" ratings occupied most of the county and areas rated "poor" were scattered throughout. These results show that the ES capacity to reduce soil erosion and resist flooding is unremarkable, despite the few "poor" areas.

#### 4.2.3. Sand Fixation Capacity

The spatial distribution of E3 trended lower in the west and higher in the east, with few areas rated "excellent" (Figure 6). The distribution of "good" ratings was also small, while "medium" areas were more densely distributed in the eastern part of the county. However, the "poor" rating applied to most of the eastern area. These results show that the county ecosystems lack sufficient ecological services to stabilise wind–sand disturbances, prevent dry–hot wind hazards, and reduce soil erosion caused by wind.

#### 4.2.4. The Spatial Distribution of the Integrated Ecosystem Services Capacity Index

The importance of water conservation capacity, soil water retention capacity, and anti-wind and sand-fixing capacity differ, but they can all be used to judge the sustainability of an ecosystem, both singly and as an integrated whole. Based on its spatial distribution, the integrated ES capacity in the study area was basically weak (Figure 7). While there were no areas with "excellent" ES capacity ratings in the county, areas with "good" ratings were located mainly in the west, and "medium" and "poor" rated areas were found throughout the county.

### *4.3. The Spatial Distribution of the Integrated Ecosystem Health Comprehensive Index*

In general, the spatial distribution of the integrated ecosystem health index showed better health in the west and worse in the east (Figure 8), but the county's overall ecosystem health was weak. Specifically, there were very few areas with "excellent" health, but there were some limited "good" health areas in the western part of the county, as well as in Xiping, Huqiu, and Daping in the south. However, "medium" and "poor" health areas were spread throughout the county, and those lowest ratings dominated the east, except for small "medium" health areas in Fengcheng and Longmen.

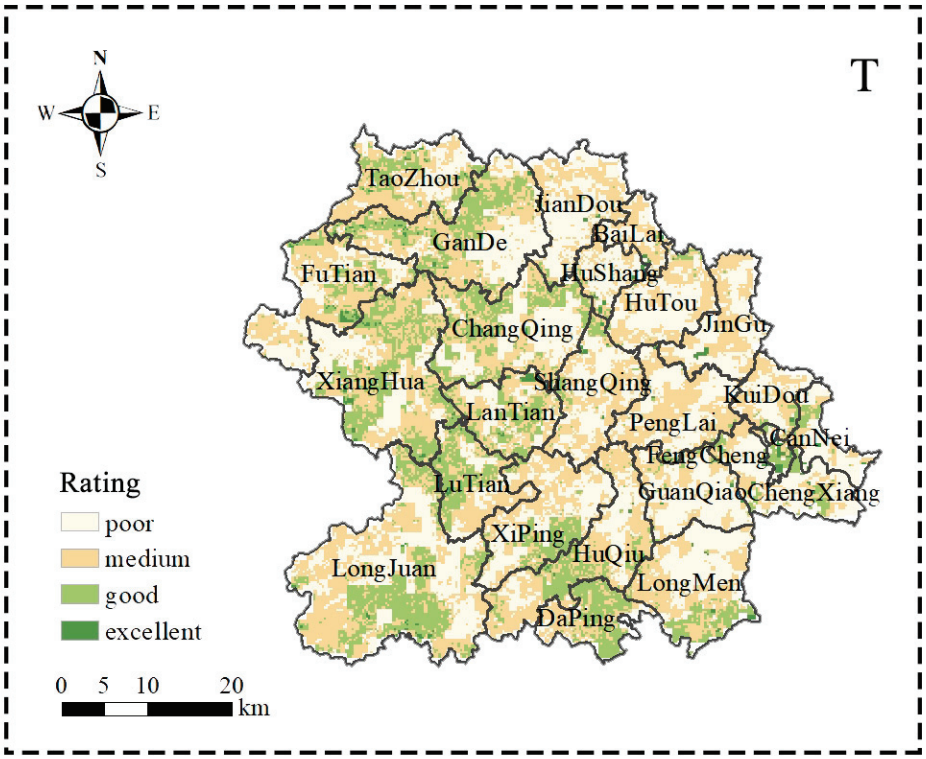



**Figure 7.** The spatial distribution of the integrated ecosystem services capacity index (T in Figure 3) for Anxi County, China.

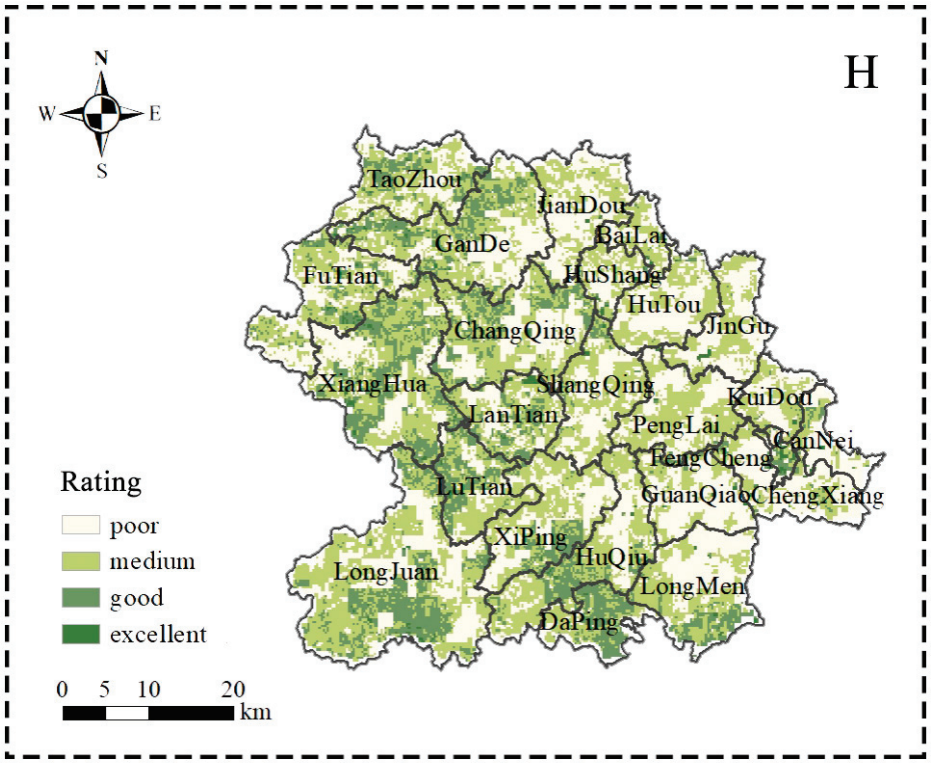



**Figure 8.** The spatial distribution of the integrated ecosystem health comprehensive index (H in Figure 3) in Anxi County, China.

## 5. Discussion

### *5.1. Traditional Forms of Ecosystem Restoration Are Facing Transformation*

Previously, protecting and restoring ecosystems focused on safeguarding individual ecological elements and addressing environmental pollution [56]. This approach enables a clearer understanding of the ecological status and operational processes of individual ecosystems, and current ecological restoration objectives typically include most of the key ecological elements in the ecosystem [57]. However, this cannot ascertain the comprehensive situation of the ecosystem. If ecological restoration persists in such a manner over an extended period, it can lead to neglected inter-ecosystem connections, which then disrupts that interconnectedness and causes destabilisation [58]. Simultaneously, such practices may heighten the exposure of ecosystems to unpredictable disaster risks and undermine their capacities for recovery and renewal [59].

Unlike most preceding studies, our study focuses on constructing an integrated assessment system for ecosystem health, which is founded on the core concept that all ecosystem types form a complex community of life. The integrated assessment framework is designed to provide guidance for our integrated restoration pathways, addressing an array of specific ecological issues. This demonstrates a distinct deviation from conventional studies that emphasize single ecosystems, and it underscores the importance of inter-ecosystem interactions and integrated restoration in maintaining ecological health and resilience. A distinctive feature of this assessment system is its ability to encompass not only the integrated key characteristic of each major ecosystem within the study area but also the integrated ecosystem service capacity.

Given the current situation, traditional forms of ecosystem restoration are facing transformation. We must establish a systematic and comprehensive restoration and governance model for interconnected ecosystems, as well as a new model of integrated ecosystem restoration. The new model should focus on the interactions between ecological elements and on the implementation of a subsequent holistic optimisation and adaptation of ecosystem structure and function. Ultimately, uncertain ecological crises are resisted, and maybe even prevented, and the integrated ecosystems as a whole are stabilised and made sustainable.

### *5.2. Integrated Pathways for Ecosystem Restoration*

Based on specific ecological problems, we propose an integrated conservation and restoration approach for the ecosystem in Anxi County, China. Subsequently, guidance is provided for the implementation of restoration pathways based on diverse comprehensive assessment levels of ecosystem health.

Firstly, our aim was to effectively maintain and improve ecosystem functions and ecological service capacities by following integrated pathways for ecosystem restoration (Figure 9).

Based on the local planning documents provided by the Anxi Natural Resources Administration and our comprehensive analysis of the primary ecological issues, we have proposed specific restoration pathways for a range of ecological problems in each ecosystem. In our example, we used the four ecosystems of Anxi County, China. Specific restoration measures for the mountain ecosystem include steps to restore mine landscapes, prevent and control geological disasters, comprehensively treat disused mines, remove loose residue, maintain repaired mountains, and change slopes to bench terraces. For the water ecosystem, water source areas should be protected; "sponge cities", ecological riverbanks, and an ecological water network should be constructed; watersheds should be comprehensively treated; and sewage treatment systems should be improved. Measures for the forest ecosystem should include enclosing hillsides for natural afforestation, managing forest resources, improving forest stands, stabilising forest community structure, protecting animal habitats, and constructing nature reserves. The cropland ecosystem measures should include constructing an agricultural forest network, transforming and improving

agricultural practices to create quality farmland with improved soil moisture and fertility, controlling agricultural pollution, and developing efficient water-saving agriculture.

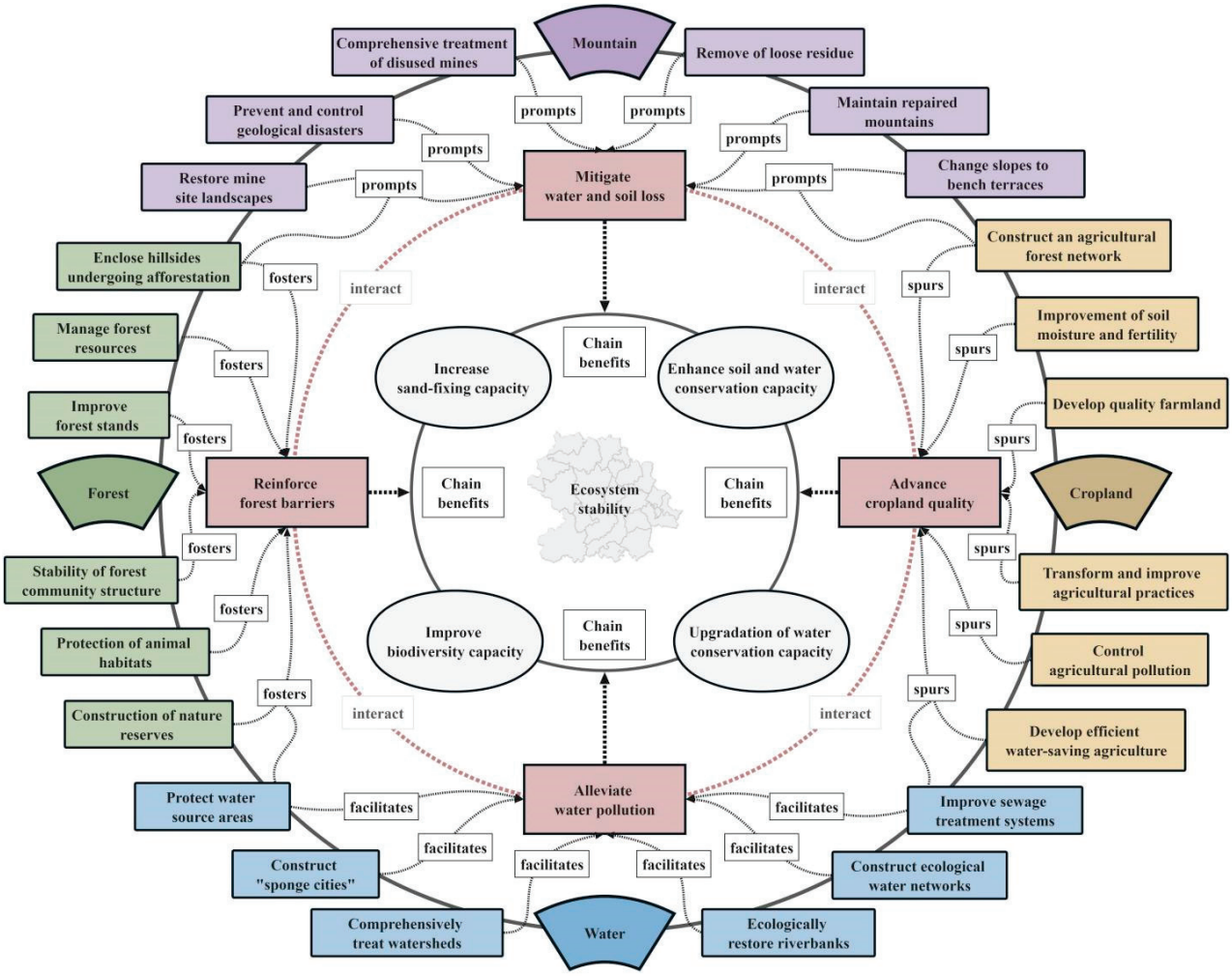



**Figure 9.** Integrated pathways for the mountain, forest, water, and cropland (outer ring) ecosystem restoration in Anxi County, China. Those solutions for each ecosystem's problems interact positively to alleviate broader problems (central ring), which then contribute to improved ecosystem service capacity and overall ecosystem stability (innermost ring).

Next, appropriate protection or restoration programmes should be developed to match the different levels of integrated ecosystem health found throughout the county. Areas with "excellent" and "good" integrated ecosystem health ratings must have their existing ecosystems protected and their overall ecological services maintained. To accomplish this, areas with natural forests and water sources must be closed to any disturbances so that new ecological damage caused by artificial modifications is avoided [60–63]. At the same time, those areas may be given vegetation buffer zones or isolation zones, and regular surveys and wildlife monitoring should be carried out [64]. In addition, harmful organisms should be eliminated or controlled to maintain good ecological functions and biodiversity [65,66]. Also, the environments surrounding restored mountains should be comprehensively protected by clarifying the scope of their protection and monitoring systems, and by formulating natural disaster prevention and control measures [67,68]. Then, to a certain extent, safety hazards may be prevented. In areas with "medium" integrated ecosystem health ratings, low-impact restoration measures should be instituted, and ecological problem prevention and control should be strengthened. If mining practices that protect the environment were adopted, serious damage to the mining regions' ecological

environments could be lessened [69]. At the same time, mine waste should be properly disposed of and production sites kept in order during the mining process [70]. Next, the riverbanks in areas rated "medium" should be softened and transformed by building ecological berms and ecological corridors [71,72]. This would both improve the ecological protection capacity and create good habitats for aquatic organisms. The areas with "poor" integrated ecosystem health ratings need integrated ecological restoration projects that address their serious ecological problems. Restoration work should focus on the holistic and systemic nature of ecosystems, and on linking and integrating the different restoration tasks in each project. In areas with important water systems and water source protection sites, sources of water pollution should be reduced and silt removed from water bodies and connecting water systems, while restoration tasks should include protecting slopes and constructing conservation forests peripheral to the water sources [73–75]. Thus, ecological problems may be solved while the surrounding areas' water storage and drainage capacities, as well as the overall ecological function of the ecosystem, are improved. Because frequent geo-disasters like landslides and ground collapses occur in the mountainous regions, it is essential that geological disaster management techniques be used to repair damaged mountains [76,77]. It is also crucial to guarantee the mountains' capacity to tolerate disasters and maintain ecological sustainability [78]. Moreover, many mountainous areas that have been converted to tea plantations experience severe soil erosion, which compounds ecological problems. Therefore, the ecosystem restoration in "poor" health mountain areas should prioritise constructing protective forests and enhancing soil quality while undertaking continuous disaster prevention and monitoring activities [79].

The primary objective of restoring and maintaining ecosystem stability and health in Anxi County is to jointly mitigate water and soil loss, reinforce forested ecological barriers, alleviate the water pollution load, and advance cropland quality by systematically protecting and restoring all ecosystems. By accomplishing this, soil water-retention capacity would be enhanced, water conservation capacity upgraded, anti-wind and sand-fixing capacity increased, and biodiversity capacity improved. In the end, the ecological service functions generate positive feedback on one another and the integrated ecosystems achieve stability and sustainability.

### *5.3. Limitations and Future Research*

Ecosystem health is a complex concept that includes not only its own state, but also depends on the capacity of ESs to support human survival. This study has constructed a comprehensive ecosystem health assessment system that combines key ecosystem characteristics and ES capacity, as well as integrated ecosystem restoration pathways for the study area. However, to make the results of the study more objective, we focused only on the natural characteristics of the ecosystem, although there is also a complex relationship between ecosystems and socio-economic systems. Common human activities that constantly affect ecosystem structure and function also precipitate changes. Therefore, further research should comprehensively explore the ecosystem health evaluation framework from a multidimensional perspective that is based on indicators with different attributes. At the same time, the applicability of ecological restoration methods for local natural conditions and integrated management approaches must be established. This would ensure the integrity of individual ecosystem elements and contribute to sustainable integrated ecosystem health. Furthermore, the primary issue to be addressed is the assessment of the integrated health level of ecosystem in this study. The selection of indicators focuses on the internal status of an ecosystem. However, developing more detailed restoration plans for different types of restoration projects requires new assessments. This encompasses the selection of indicators that can reflect the diverse ecological issues within each ecosystem, as well as the assessment of the effectiveness of the integrated ecosystem health index in this study. This is also an aspect that deserves continued in-depth exploration in our future study.

## 6. Conclusions

Based on the perspective that the ecosystem is a community of life, this study used key characteristic ecosystem and ES capacity indicators to construct an integrated assessment system that examined the health of the ecosystems in the study area: Anxi County, China. Then, we identified the ecological problems that exist in each of the area's four ecosystems and used them to propose integrated pathways for restoring those ecosystems. Ultimately, the integrated index assessment results can guide the development of ecological restoration models tailored to different regions. The integrated assessment of the ecosystems' key characteristics revealed that most areas in the county had an overall weak self-recovery potential. The integrated assessment of ES capacity also showed that most of the county's areas had a generally weak overall ES capacity. According to the integrated ecosystem health assessment, the overall ratings trend was higher in the west and lower in the east, but as a whole, the county's ecosystem health was weak. Therefore, conservation and restoration programmes based on comprehensive assessments should be implemented in different areas. In the areas with better integrated ecosystem health, the overriding need is to protect the ecosystems and maintain their overall ESs. In moderately healthy areas, low-impact restoration measures should be enacted, as well as a strengthening of the prevention and control of ecological problems. In the areas with the worst ecosystem health, integrated ecological restoration projects are needed to address serious ecological problems. Also, the restoration process should consider the realistic ecological challenges of the diverse ecosystems in the area and ensure the connectivity and coordination of each restoration task. This approach benefits the maintenance of ecosystem stability and an enhanced sustainability of ES.

**Author Contributions:** Conceptualization, T.Z., C.W., S.Z., Y.W. and H.W.; investigation, T.Z., S.Z., C.W., H.W. and Y.W.; resources, S.Z., C.W. and T.Z.; methodology, T.Z., Y.W. and C.W.; data curation, T.Z., S.Z. and C.W.; software, T.Z.; validation, Y.W., C.W. and T.Z.; visualization, T.Z.; formal analysis, T.Z.; writing—original draft preparation, T.Z.; writing—review and editing, T.Z., S.Z., C.W., Y.W. and H.W.; supervision, H.W. and Y.W.; project administration, H.W. and S.Z.; funding acquisition, H.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Science and Technology Planning Project of Fujian Province, China (2022H0044).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data are not publicly available due to the collaborative nature of this study with the local government.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Costanza, R. Ecosystem health and ecological engineering. *Ecol. Eng.* **2012**, *45*, 24–29. [CrossRef]
2. Jenerette, G.D. Ecological contributions to human health in cities. *Landsc. Ecol.* **2018**, *33*, 1655–1668. [CrossRef]
3. Zhang, Z.; Chang, J.; Xu, C.-Y.; Zhou, Y.; Wu, Y.; Chen, X.; Jiang, S.; Duan, Z. The response of lake area and vegetation cover variations to climate change over the Qinghai-Tibetan Plateau during the past 30years. *Sci. Total Environ.* **2018**, *635*, 443–451. [CrossRef]
4. Zou, F.; Li, H.; Hu, Q. Responses of vegetation greening and land surface temperature variations to global warming on the Qinghai-Tibetan Plateau, 2001–2016. *Ecol. Indic.* **2020**, *119*, 106867. [CrossRef]
5. Li, W.; Xie, S.; Wang, Y.; Huang, J.; Cheng, X. Effects of urban expansion on ecosystem health in Southwest China from a multi-perspective analysis. *J. Clean. Prod.* **2021**, *294*, 126341. [CrossRef]
6. Manuel-Navarrete, D.; Gómez, J.J.; Gallopín, G. Syndromes of sustainability of development for assessing the vulnerability of coupled human–environmental systems. The case of hydrometeorological disasters in Central America and the Caribbean. *Glob. Environ. Change* **2007**, *17*, 207–217. [CrossRef]
7. Costanza, R.; de Groot, R.; Sutton, P.; van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the global value of ecosystem services. *Glob. Environ. Change* **2014**, *26*, 152–158. [CrossRef]

8. Gashaw, T.; Tulu, T.; Argaw, M.; Worqlul, A.W.; Tolessa, T.; Kindu, M. Estimating the impacts of land use/land cover changes on Ecosystem Service Values: The case of the Andassa watershed in the Upper Blue Nile basin of Ethiopia. *Ecosyst. Serv.* **2018**, *31*, 219–228. [CrossRef]
9. Connell, D.J. Sustainable Livelihoods and Ecosystem Health: Exploring Methodological Relations as a Source of Synergy. *EcoHealth* **2010**, *7*, 351–360. [CrossRef]
10. Yang, Y.; Song, G.; Lu, S. Assessment of land ecosystem health with Monte Carlo simulation: A case study in Qiqihaer, China. *J. Clean. Prod.* **2020**, *250*, 119522. [CrossRef]
11. Xu, L.; Xie, X. Theoretic Research on the Relevant Concepts of Urban Ecosystem Carrying Capacity. *Procedia Environ. Sci.* **2012**, *13*, 863–872. [CrossRef]
12. Chen, W.; Wang, G.; Zeng, J. Impact of urbanization on ecosystem health in Chinese urban agglomerations. *Environ. Impact Assess. Rev.* **2023**, *98*, 106964. [CrossRef]
13. Xiao, R.; Liu, Y.; Fei, X.; Yu, W.; Zhang, Z.; Meng, Q. Ecosystem health assessment: A comprehensive and detailed analysis of the case study in coastal metropolitan region, eastern China. *Ecol. Indic.* **2019**, *98*, 363–376. [CrossRef]
14. Su, M.; Xie, H.; Yue, W.; Zhang, L.; Yang, Z.; Chen, S. Urban ecosystem health evaluation for typical Chinese cities along the Belt and Road. *Ecol. Indic.* **2019**, *101*, 572–582. [CrossRef]
15. O'Brien, A.; Townsend, K.; Hale, R.; Sharley, D.; Pettigrove, V. How is ecosystem health defined and measured? A critical review of freshwater and estuarine studies. *Ecol. Indic.* **2016**, *69*, 722–729. [CrossRef]
16. Su, M.; Fath, B.D.; Yang, Z. Urban ecosystem health assessment: A review. *Sci. Total Environ.* **2010**, *408*, 2425–2434. [CrossRef]
17. Douglas, I. Urban ecology and urban ecosystems: Understanding the links to human health and well-being. *Curr. Opin. Environ. Sustain.* **2012**, *4*, 385–392. [CrossRef]
18. Bao, Z.; Shifaw, E.; Deng, C.; Sha, J.; Li, X.; Hanchiso, T.; Yang, W. Remote sensing-based assessment of ecosystem health by optimizing vigor-organization-resilience model: A case study in Fuzhou City, China. *Ecol. Inform.* **2022**, *72*, 101889. [CrossRef]
19. Lv, T.; Zeng, C.; Lin, C.; Liu, W.; Cheng, Y.; Li, Y. Towards an integrated approach for land spatial ecological restoration zoning based on ecosystem health assessment. *Ecol. Indic.* **2023**, *147*, 110016. [CrossRef]
20. Khatun, R.; Das, S. Exploring ecosystem health of wetlands in Rarh tract of West Bengal through V-O-R model. *Ecol. Inform.* **2022**, *72*, 101840. [CrossRef]
21. Das, M.; Das, A.; Mandal, A. Research note: Ecosystem Health (EH) assessment of a rapidly urbanizing metropolitan city region of eastern India—A study on Kolkata Metropolitan Area. *Landsc. Urban Plan.* **2020**, *204*, 103938. [CrossRef]
22. Lei, J.; Li, C.; Yang, W. Ecosystem health assessment and approaches to improve Sichuan Province based on an improved vigor organization resilience model. *Ecol. Indic.* **2023**, *155*, 110925. [CrossRef]
23. O'Leary, B.C.; Fonseca, C.; Cornet, C.C.; de Vries, M.B.; Degia, A.K.; Failler, P.; Furlan, E.; Garrabou, J.; Gil, A.; Hawkins, J.P.; et al. Embracing Nature-based Solutions to promote resilient marine and coastal ecosystems. *Nat. Based Solut.* **2023**, *3*, 100044. [CrossRef]
24. Basconi, L.; Rova, S.; Stocco, A.; Pranovi, F. Ecosystem services for supporting coastal and marine resources management, an example from the Adriatic sea (Central Mediterranean sea). *Ocean Coast. Manag.* **2023**, *235*, 106486. [CrossRef]
25. Shen, W.; Li, Y.; Qin, Y.; Cheng, J. Influencing mechanism of climate and human activities on ecosystem health in the middle reaches of the Yellow River of China. *Ecol. Indic.* **2023**, *150*, 110191. [CrossRef]
26. Li, T.; Wang, H.; Fang, Z.; Liu, G.; Zhang, F.; Zhang, H.; Li, X. Integrating river health into the supply and demand management framework for river basin ecosystem services. *Sustain. Prod. Consum.* **2022**, *33*, 189–202. [CrossRef]
27. Cai, H.; Lu, H.; Tian, Y.; Liu, Z.; Huang, Y.; Jian, S. Effects of invasive plants on the health of forest ecosystems on small tropical coral islands. *Ecol. Indic.* **2020**, *117*, 106656. [CrossRef]
28. Ishtiaque, A.; Myint, S.W.; Wang, C. Examining the ecosystem health and sustainability of the world's largest mangrove forest using multi-temporal MODIS products. *Sci. Total Environ.* **2016**, *569–570*, 1241–1254. [CrossRef]
29. Halperin, S.; Castro, A.J.; Quintas-Soriano, C.; Brandt, J.S. Assessing high quality agricultural lands through the ecosystem services lens: Insights from a rapidly urbanizing agricultural region in the western United States. *Agric. Ecosyst. Environ.* **2023**, *349*, 108435. [CrossRef]
30. Chi, Y.; Zheng, W.; Shi, H.; Sun, J.; Fu, Z. Spatial heterogeneity of estuarine wetland ecosystem health influenced by complex natural and anthropogenic factors. *Sci. Total Environ.* **2018**, *634*, 1445–1462. [CrossRef]
31. Horwitz, P.; Finlayson, C.M. Wetlands as Settings for Human Health: Incorporating Ecosystem Services and Health Impact Assessment into Water Resource Management. *BioScience* **2011**, *61*, 678–688. [CrossRef]
32. Alrawaf, T.I.; Abubakar, I.R.; Alshabibi, N.M.; Al-Matar, K.M.; Dano, U.L.; Elhadi, E.M.A.; Farooqi, M.A.; Alshihri, F.S.; Alzenifeer, B.M.; Al-Odah, M.A. The distribution of ecotourism activities and potential consequences for the Saudi desert ecosystem. *J. Arid Environ.* **2023**, *213*, 104950. [CrossRef]
33. Bryan, B.A.; Gao, L.; Ye, Y.; Sun, X.; Connor, J.D.; Crossman, N.D.; Stafford-Smith, M.; Wu, J.; He, C.; Yu, D.; et al. China's response to a national land-system sustainability emergency. *Nature* **2018**, *559*, 193–204. [CrossRef]
34. Yu, Q.; Lu, H.; Yao, T.; Xue, Y.; Feng, W. Enhancing sustainability of vegetation ecosystems through ecological engineering: A case study in the Qinghai-Tibet Plateau. *J. Environ. Manag.* **2023**, *325*, 116576. [CrossRef] [PubMed]
35. Xu, D.; Wang, Y.; Wang, Z. Linking priority areas and land restoration options to support desertification control in northern China. *Ecol. Indic.* **2022**, *137*, 108747. [CrossRef]

36. Bao, T.; Li, J.; Chang, I.S.; Jin, E.; Wu, J.; Burenjargal; Bao, Y. The influence of ecological engineering projects on dust events: A case study in the northern China. *Environ. Impact Assess. Rev.* **2022**, *96*, 106847. [CrossRef]
37. Luo, K. Response of hydrological systems to the intensity of ecological engineering. *J. Environ. Manag.* **2021**, *296*, 113173. [CrossRef]
38. Li, Z.; Ning, K.; Chen, J.; Liu, C.; Wang, D.; Nie, X.; Hu, X.; Wang, L.; Wang, T. Soil and water conservation effects driven by the implementation of ecological restoration projects: Evidence from the red soil hilly region of China in the last three decades. *J. Clean. Prod.* **2020**, *260*, 121109. [CrossRef]
39. Liao, C.; Yue, Y.; Wang, K.; Fensholt, R.; Tong, X.; Brandt, M. Ecological restoration enhances ecosystem health in the karst regions of southwest China. *Ecol. Indic.* **2018**, *90*, 416–425. [CrossRef]
40. Tang, D.; Liu, X.; Zou, X. An improved method for integrated ecosystem health assessments based on the structure and function of coastal ecosystems: A case study of the Jiangsu coastal area, China. *Ecol. Indic.* **2018**, *84*, 82–95. [CrossRef]
41. Wu, S.; Li, D.; Wang, X.; Li, S. Examining component-based city health by implementing a fuzzy evaluation approach. *Ecol. Indic.* **2018**, *93*, 791–803. [CrossRef]
42. Yang, T.; Liu, J.; Chen, Q. Assessment of plain river ecosystem function based on improved gray system model and analytic hierarchy process for the Fuyang River, Haihe River Basin, China. *Ecol. Model.* **2013**, *268*, 37–47. [CrossRef]
43. Wu, M.; Wei, Y.; Lam, P.T.I.; Liu, F.; Li, Y. Is urban development ecologically sustainable? Ecological footprint analysis and prediction based on a modified artificial neural network model: A case study of Tianjin in China. *J. Clean. Prod.* **2019**, *237*, 117795. [CrossRef]
44. Shen, W.; Zheng, Z.; Pan, L.; Qin, Y.; Li, Y. A integrated method for assessing the urban ecosystem health of rapid urbanized area in China based on SFPHD framework. *Ecol. Indic.* **2021**, *121*, 107071. [CrossRef]
45. Yu, H.; Zahidi, I. Spatial and temporal variation of vegetation cover in the main mining area of Qibaoshan Town, China: Potential impacts from mining damage, solid waste discharge and land reclamation. *Sci. Total Environ.* **2023**, *859*, 160392. [CrossRef]
46. Zhao, J.; Ji, G.; Tian, Y.; Chen, Y.; Wang, Z. Environmental vulnerability assessment for mainland China based on entropy method. *Ecol. Indic.* **2018**, *91*, 410–422. [CrossRef]
47. Cheng, W.; Xi, H.; Sindikubwabo, C.; Si, J.; Zhao, C.; Yu, T.; Li, A.; Wu, T. Ecosystem health assessment of desert nature reserve with entropy weight and fuzzy mathematics methods: A case study of Badain Jaran Desert. *Ecol. Indic.* **2020**, *119*, 106843. [CrossRef]
48. Liu, X.; Wang, Y.; Meng, X.; Zhang, C.; Chen, Z. Improved method for benthic ecosystem health assessment by integrating chemical indexes into multiple biological indicator species—A case study of the Baiyangdian Lake, China. *J. Environ. Manag.* **2023**, *335*, 117530. [CrossRef]
49. Ren, Y.; Zhang, F.; Li, J.; Zhao, C.; Jiang, Q.; Cheng, Z. Ecosystem health assessment based on AHP-DPSR model and impacts of climate change and human disturbances: A case study of Liaohe River Basin in Jilin Province, China. *Ecol. Indic.* **2022**, *142*, 109171. [CrossRef]
50. Tolessa, T.; Senbeta, F.; Kidane, M. The impact of land use/land cover change on ecosystem services in the central highlands of Ethiopia. *Ecosyst. Serv.* **2017**, *23*, 47–54. [CrossRef]
51. Vollmer, D.; Burkhard, K.; Adem Esmail, B.; Guerrero, P.; Nagabhatla, N. Incorporating Ecosystem Services into Water Resources Management—Tools, Policies, Promising Pathways. *Environ. Manag.* **2022**, *69*, 627–635. [CrossRef] [PubMed]
52. Pan, Z.; He, J.; Liu, D.; Wang, J.; Guo, X. Ecosystem health assessment based on ecological integrity and ecosystem services demand in the Middle Reaches of the Yangtze River Economic Belt, China. *Sci. Total Environ.* **2021**, *774*, 144837. [CrossRef]
53. Juntti, M.; Lundy, L. A mixed methods approach to urban ecosystem services: Experienced environmental quality and its role in ecosystem assessment within an inner-city estate. *Landsc. Urban Plan.* **2017**, *161*, 10–21. [CrossRef]
54. Hasani, M.; Pielesiak, I.; Mahiny, A.S.; Mikaeili, A. Regional ecosystem health assessment based on landscape patterns and ecosystem services approach. *Acta Ecol. Sin.* **2023**, *43*, 333–342. [CrossRef]
55. Zongfan, B.; Ling, H.; Xuhai, J.; Ming, L.; Liangzhi, L.; Huiqun, L.; Jiaxin, L. Spatiotemporal evolution of desertification based on integrated remote sensing indices in Duolun County, Inner Mongolia. *Ecol. Inform.* **2022**, *70*, 101750. [CrossRef]
56. Wang, Z.; Daun, C.; Yuan, L.; Rao, J.; Zhou, Z.; Li, J.; Yang, C.; Xu, W. Assessment of the restoration of a degraded semi-humid evergreen broadleaf forest ecosystem by combined single-indicator and comprehensive model method. *Ecol. Eng.* **2010**, *36*, 757–767. [CrossRef]
57. Li, Z.; Zhai, Y.; Zhang, T.; Zhou, X.; Cheng, Z.; Xu, T.; Li, C.; Hong, J. How can ecosystem status be more comprehensively reflected? A case study of Jinan City, China. *Sci. Total Environ.* **2023**, *863*, 160970. [CrossRef]
58. Tao, Q.; Gao, G.; Xi, H.; Wang, F.; Cheng, X.; Ou, W.; Tao, Y. An integrated evaluation framework for multiscale ecological protection and restoration based on multi-scenario trade-offs of ecosystem services: Case study of Nanjing City, China. *Ecol. Indic.* **2022**, *140*, 108962. [CrossRef]
59. Tian, M.; Gao, J.; Song, G.; Feng, C. Prioritizing ecological conservation strategies to enhance national ecological connectivity in China. *Ecol. Indic.* **2023**, *150*, 110273. [CrossRef]
60. Liu, F.; Feng, C.; Zhou, Y.; Zhang, L.; Du, J.; Huang, W.; Luo, J.; Wang, W. Effectiveness of functional zones in National Nature Reserves for the protection of forest ecosystems in China. *J. Environ. Manag.* **2022**, *308*, 114593. [CrossRef]
61. Zhao, H.; Wu, R.; Long, Y.; Hu, J.; Yang, F.; Jin, T.; Wang, J.; Hu, P.; Wu, W.; Diao, Y.; et al. Individual-level performance of nature reserves in forest protection and the effects of management level and establishment age. *Biol. Conserv.* **2019**, *233*, 23–30. [CrossRef]

62. Zeng, Y.; Meng, S.; Wu, Q.; Mei, A.; Bu, W. Ecological water security impact of large coal base development and its protection. *J. Hydrol.* **2023**, *619*, 129319. [CrossRef]
63. Qi, X.; Zhang, Z.; Jing, J.; Hu, W.; Zhao, X. Regional planning for ecological protection of rivers in highly urbanized areas. *Ecol. Indic.* **2023**, *149*, 110158. [CrossRef]
64. Zhan, C.; Liang, C.; Zhao, L.; Jiang, S.; Niu, K.; Zhang, Y.; Cheng, L. Detection and attribution of vegetation dynamics in the National Barrier Zone of China by considering climate temporal effects. *Int. J. Appl. Earth Obs. Geoinf.* **2023**, *116*, 103140. [CrossRef]
65. Fahad, S.; Saud, S.; Akhter, A.; Bajwa, A.A.; Hassan, S.; Battaglia, M.; Adnan, M.; Wahid, F.; Datta, R.; Babur, E.; et al. Bio-based integrated pest management in rice: An agro-ecosystems friendly approach for agricultural sustainability. *J. Saudi Soc. Agric. Sci.* **2021**, *20*, 94–102. [CrossRef]
66. Verga, E.G.; Huais, P.Y.; Herrero, M.L. Population responses of pest birds across a forest cover gradient in the Chaco ecosystem. *For. Ecol. Manag.* **2021**, *491*, 119174. [CrossRef]
67. Liu, Y.; Liu, H.; Yan, C.; Feng, Z.; Zhou, S. Evaluation and dynamic monitoring of ecological environment quality in mining area based on improved CRSEI index model. *Heliyon* **2023**, *9*, e20787. [CrossRef] [PubMed]
68. Souza-Filho, P.W.M.; Cavalcante, R.B.L.; Nascimento, W.R.; Nunes, S.; Gastauer, M.; Santos, D.C.; Silva, R.O.; Sahoo, P.K.; Salomão, G.; Silva, M.S.; et al. The sustainability index of the physical mining Environment in protected areas, Eastern Amazon. *Environ. Sustain. Indic.* **2020**, *8*, 100074. [CrossRef]
69. Harford, A.J.; Bartolo, R.E.; Humphrey, C.L.; Nicholson, J.D.; Richardson, D.L.; Rissik, D.; Iles, M.; Dambacher, J.M. Resolving ecosystem complexity in ecological risk assessment for mine site rehabilitation. *J. Environ. Manag.* **2022**, *319*, 115488. [CrossRef] [PubMed]
70. Zhao, W.; Wu, S.; Chen, X.; Shen, J.; Wei, F.; Li, D.; Liu, L.; Li, S. How would ecological restoration affect multiple ecosystem service supplies and tradeoffs? A study of mine tailings restoration in China. *Ecol. Indic.* **2023**, *153*, 110451. [CrossRef]
71. Chen, R.; Carruthers-Jones, J.; Carver, S.; Wu, J. Constructing urban ecological corridors to reflect local species diversity and conservation objectives. *Sci. Total Environ.* **2023**, *907*, 167987. [CrossRef]
72. Peng, J.; Zhao, H.; Liu, Y. Urban ecological corridors construction: A review. *Acta Ecol. Sin.* **2017**, *37*, 23–30. [CrossRef]
73. Lyu, L.; Bi, S.; Yang, Y.; Zheng, D.; Li, Q. Effects of vegetation distribution and landscape pattern on water conservation in the Dongjiang River basin. *Ecol. Indic.* **2023**, *155*, 111017. [CrossRef]
74. Hou, G.; Zheng, J.; Cui, X.; He, F.; Zhang, Y.; Wang, Y.; Li, X.; Fan, C.; Tan, B. Suitable coverage and slope guided by soil and water conservation can prevent non-point source pollution diffusion: A case study of grassland. *Ecotoxicol. Environ. Saf.* **2022**, *241*, 113804. [CrossRef] [PubMed]
75. Sun, Z.; Feng, M.; Zhang, X.; Zhang, S.; Zhang, W.; Li, Y.; Huang, Y.; Qi, P.; Wang, W.; Zou, Y.; et al. A healthier water use strategy in primitive forests contributes to stronger water conservation capabilities compared with secondary forests. *Sci. Total Environ.* **2022**, *851*, 158290. [CrossRef] [PubMed]
76. Zhang, J.; Zhang, J.; Deng, Y.; Wu, C.; Li, H.; Qing, Z.; Li, J.; Zhang, W. Quantitative evaluation of ecological and environmental impacts caused by future mining. *Ore Geol. Rev.* **2023**, *162*, 105672. [CrossRef]
77. Guan, Y.; Wang, J.; Zhou, W.; Bai, Z.; Cao, Y. Delimiting supervision zones to inform the revision of land reclamation management modes in coal mining areas: A perspective from the succession characteristics of rehabilitated vegetation. *Land Use Policy* **2023**, *131*, 106729. [CrossRef]
78. Yu, Y.; Li, J.; Han, L.; Zhang, S. Research on ecological compensation based on the supply and demand of ecosystem services in the Qinling-Daba Mountains. *Ecol. Indic.* **2023**, *154*, 110687. [CrossRef]
79. Guo, K.; Zhang, X.; Liu, J.; Wu, Z.; Chen, M.; Zhang, K.; Chen, Y. Establishment of an integrated decision-making method for planning the ecological restoration of terrestrial ecosystems. *Sci. Total Environ.* **2020**, *741*, 139852. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

Article

# The Restorative Potential of Green Cultural Heritage: Exploring Cultural Ecosystem Services' Impact on Stress Reduction and Attention Restoration

**Jing Xie [1], Shixian Luo [2], Katsunori Furuya [1,*], Huixin Wang [1], Jiao Zhang [1], Qian Wang [1], Hongyu Li [1] and Jie Chen [1]**

[1] Graduate School of Horticulture, Chiba University, Chiba 271-8510, Japan; 21hd5402@student.gs.chiba-u.jp (J.X.); wanghuixin1229@yeah.net (H.W.); 20hd5401@student.gs.chiba-u.jp (J.Z.); mayu.wq@gmail.com (Q.W.); aysa5422@chiba-u.jp (H.L.); cdga0939@chiba-u.jp (J.C.)
[2] School of Architecture, Southwest Jiaotong University, Chengdu 611756, China; shixianluo@swjtu.edu.cn
* Correspondence: k.furuya@faculty.chiba-u.jp

**Abstract:** Green cultural heritage is an important form of natural space in cities. Only a few studies have conducted restorative studies in a historical environment as most have focused on natural environments. Moreover, few studies on cultural ecosystem services (CESs) have addressed cultural heritage. Based on an onsite questionnaire distributed to green cultural heritage users (N = 64) in Hamarikyu Garden, this paper explores the value of CESs in a green cultural heritage site and the relationship between cultural ecosystem values and perceived attention restoration/stress reduction. A multiple linear regression analysis and simple linear regression analyses were used to examine the data. The results showed that (1) the cultural ecosystem values of the green cultural heritage site were all rated highly except for the sense of place; (2) spending time in green cultural heritage provided respondents significant perceived attention restoration and stress reduction; (3) aesthetics and cultural heritage significantly affected perceived stress reduction, while attention restoration showed a significant positive correlation with aesthetic value and sense of place; and (4) the more visitors perceived the value of CESs, the more significant the perceived stress reduction and attention recovery were. This study indicates that CESs represent a useful tool for measuring the environmental characteristics of green cultural heritage sites and can predict perceived psychological recovery in green cultural heritage sites. Our findings enhance our knowledge about restorative environmental attributes through objective descriptions of potential health-promoting qualities and can be utilized as inspiration for designing restorative environments in green cultural heritage sites.

**Keywords:** perceived mental recovery; attention restoration theory; stress reduction theory; cultural ecosystem services; green cultural heritage

**Citation:** Xie, J.; Luo, S.; Furuya, K.; Wang, H.; Zhang, J.; Wang, Q.; Li, H.; Chen, J. The Restorative Potential of Green Cultural Heritage: Exploring Cultural Ecosystem Services' Impact on Stress Reduction and Attention Restoration. *Forests* **2023**, *14*, 2191. https://doi.org/10.3390/f14112191

Academic Editor: Xin-Chen Hong

Received: 1 October 2023
Revised: 24 October 2023
Accepted: 2 November 2023
Published: 3 November 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Cultural heritage refers to the tangible and intangible heritage assets passed down from generation to generation by a group or society [1]. However, not all assets passed through the ages are considered "heritage"; rather, heritage is specifically the product of social choices [2]. When assessing cultural heritage, it is important to consider its intrinsic value in terms of its links with sustainable development [3,4]. This intrinsic value encompasses the ability to convey the values and meanings of the past and serves as a living memory of the local ecosystem [5]. It also conveys the intangible meaning of the heritage site, including the quality of the place and the emotional attachment people develop to it [6].

Scholars in architecture, planning, travel, and other related disciplines have conducted many studies on cultural heritage, such as those related to urban planning in World Heritage Cities [4,7]; the architecture of heritage buildings [8,9]; and heritage tourism [10–12].

However, cultural heritage includes not only buildings and structures but also culturally significant landscapes and natural environments that are often overlooked by scholars.

The inclusion of landscapes in the domain of heritage is the result of an allegorical expansion of heritage throughout the 20th century [13]. Landscape architecture implies an understanding of the concept of territory as a social outcome. It involves the introduction of historical elements that make landscape architecture a product with evolutionary and transformative dimensions [2]. Although landscape architecture is the creator of green cultural heritage (an environment combining nature and history) [14], research on green cultural heritage (GCH) remains limited. The semantic expansion of heritage to include landscapes was introduced [13], giving rise to the concept of green cultural heritage, which emphasizes the importance of preserving natural and cultural landscapes. In addition, green cultural heritage (which is not yet strictly defined), according to Bučas (2006), is a type of heritage created with the use of living natural materials (e.g., plants, flowers) rather than human-made materials; green cultural heritage sites are created by modifying the green elements of nature according to human ideas [14]. This kind of place, where humans and nature coexist harmoniously, is not just about ecological arboriculture; nor is it just about an architectural site. Therefore, these areas should be referred to as green cultural heritage sites, considering their nature and purpose as serious spiritual places conducive to communication and a quiet connection with nature [14]. GCH sites are important green infrastructure in cities, and numerous studies have demonstrated the restorative benefits of green spaces. Several scholarly efforts have been made to study the landscape quality, health, and well-being of CGH sites. For example, Deng et al. (2020) found that the effects of three landscape types and various elements of a traditional park on psychophysiological activities were investigated using physiological and psychological indicators [15]; Luo et al. (2022) investigated restorative experience in the pavilions of a GCH site [16]. However, research on the restorative experience encompassing both the stress reduction and attention restoration effects of GCH sites has been neglected. In addition to the restorative qualities of a green space's natural elements, some studies have begun to explore the perceived restorative benefits that cultural and historical elements provide users; however, very little research has been carried out on green spaces with historical and cultural ambience. Therefore, the effective usage of this neglected green asset in cities can play an important role in the development of healthy cities. Additionally, little attention has been paid to the cultural ecosystem services (CESs) of urban cultural heritage, and established research has overemphasized people's experience of the natural environment in urban spaces rather than the cultural environment. Thus, there is a gap in research on the relationship between restorative experiences and perceived CESs in GCH sites.

Starting from the above considerations, this study aims to examine the restorative potential of GCH sites and explore the impact of CESs on stress reduction and attention restoration; furthermore, the associations between perceived CESs and restorative experiences (perceived stress reduction and perceived attention restoration) were explored. Following the Introduction in Section 1, Section 2 discusses the theoretical background and conceptualization of CESs, the SRT, and the ART and the development of a hypothesis. Section 3 then provides a detailed discussion of the methods used. Section 4 presents the findings of this study, while Section 5 presents a discussion. Finally, Section 6 discusses the conclusion, implications, limitations, and future research suggestions.

## 2. Literature Review

### *2.1. Current Research on Cultural Ecosystem Services Ignores Cultural Heritage*

There is consensus that the urban ecosystem services provided by green spaces not only support sustainable urban development but also improve environmental quality and human health and well-being. The Millennium Ecosystem Assessment (MA) was initiated by the United Nations and Global Environment Facility in 2001 to assess the state of the world's ecosystem services and formulate protection programs [17]. To quantify the benefits obtained from ecosystem functions, the MA proposed the concept of ecosystem services

and divided it into four categories: regulating, supporting, supplying, and cultural services. In more detail, nature provides us with water, clean air, and food, as well as raw materials for medicine, industry, and construction. In addition, enjoying parks, landscapes, and wildlife improves our health and well-being. All these benefits are called ecosystem services. Ecosystem services are therefore the direct and indirect contributions that ecosystems make to human well-being and quality of life.

Cultural ecosystem services (CESs), as a subcategory of ecosystem services, focus on the scope of cultural services. CESs are defined as the "non-material" benefits that people derive from ecosystems, such as aesthetic information, recreation, spirituality, enrichment, or cultural heritage [17,18]. Such non-material CESs arise from human interactions with the biophysical environment. Although the importance of CESs is generally recognized, its assessment lags behind that of more specific services [19,20] because its subjective value is intangible. Therefore, the quantification of CESs is difficult in biophysical or monetary terms [21], and its values may vary according to an individual's social and cultural norms [22]. From this perspective, the evaluation of CESs requires extracting complementary capabilities and methods from the social sciences and humanities [23].

Current CES research overemphasizes people's experiences of nature in urban spaces. For example, Kremer et al. (2016) [24] argued that CESs are the most important ecosystem services for urban dwellers because they represent some of people's most familiar and personal experiences of nature in urban environments, which may inspire a willingness to protect the natural environment and influence conservation practices [25]. Furthermore, the CES values provided by urban parks have received widespread attention [17,26,27]. Larson et al. (2016) referred to CES values in urban greenways [28]. Dickinson and Hobbs (2017) focused on the importance of CESs in urban green spaces for urban residents and the role of management in urban green spaces [29]. While some scholars have noted the CESs provided by urban green infrastructure [30], only a few have identified their value potential in cultural heritage and the impact of CES values on human well-being [31] and cultural heritage management [32].

Schaich et al. (2010) argued that the evaluation of CESs is an assessment method that goes beyond purely economic values by integrating social and humanistic approaches, which can establish new research frameworks in the field of heritage [33]. CES assessments can detect features that are beneficial to people from the perspective of cultural landscapes and thus understand their potential for sustainable development [31]. In addition, the management of cultural heritage can gain traction through CES evaluations as they can assess the potential of a site or area in terms of human well-being [18,32]. When considering the current needs of cultural heritage research, it is pertinent to explore the link between cultural heritage and CESs. Despite the emphasis on the benefits of CES research for cultural heritage [2], current research on CESs continues to focus on natural experiences at the expense of cultural landscapes.

### *2.2. Absent Studies of Restorative Potential in GCH*

Currently, urban life generates many physical health problems and mental stresses such as disease and cancer. Residents living in large cities (e.g., London, New York, Tokyo) may experience physical and psychological stresses that reduce their personal quality of life [34–36]. Over the past four decades, a growing body of research has shown that urban green spaces are an important resource for public health as they can have a restorative effect on cognitive processes [37] and help relieve stress [38]. In this context, the stress reduction theory (SRT [39]) and attention restoration theory (ART [40]) have emerged as major approaches to explaining the restorative benefits of natural experiences and are frequently used restorative theories today [16,41–43].

For Ulrich et al. (1991), the SRT is a psychological evolutionary model that focuses on the physical environment [39]. It emphasizes the importance of recovery from psychological and physiological stresses associated with threats or challenges based on emotional

functioning [16,44]. Therefore, an individual's experience of relaxation, escape from daily worries, and calmness can be considered a reduction in perceived stress [45].

The ART emphasizes the importance of recovery from attentional fatigue based on cognitive functioning. Kaplan (1995) categorized the restorative characteristics of the ART into four components: fascination, being away, extent, and compatibility, with the understanding that the depletion of directed attention can be restored through exposure to a natural environment [40]. The understanding of the ART distinguishes between two attentional mechanisms of attentional patterns: "directed" and "effortless" [46]. Thus, the state of reduced directed attention fatigue based on cognitive functioning is a restorative experience (subjective-measure outcomes of such experiences can be termed "perceived attention restoration" [44]).

Restoration properties can manifest in a range of environments, from completely natural to fully constructed. Kaplan and Kaplan (1989), for example, clearly stated that a high-level built environment also has some restoration potential [47]. Currently, there are fewer studies on the restoration potential of the built environment than there are on the restoration potential of the natural environment [46]; however, studies examining the built environment are gradually receiving more scholarly attention. Kaplan (1993) found that museum environments have some restorative potential [48]; subsequently, Packer and Bond (2010) found that museums can also have the same restorative qualities as natural environments [49]. Abdulkarim and Nasar (2014) found that certain architectural elements, such as sculptures and seating, also made sites more restorative [41]. Hidalgo et al. (2006) found that people's preferred built environments (historical/cultural and recreational sites) were also restorative [50]. Ulrich et al. (1991) found that natural environments are more restorative than man-made environments in emotional and physical terms [39]. In addition to natural or built environments, the restoration potential of mixed natural and historic environments should also be investigated [51]. Historic green spaces in cities are green cultural heritage sites that blend nature and historic culture. It is worthwhile to investigate the restorative potential for people in environments containing both natural and historical characteristics (i.e., green cultural heritage sites).

### *2.3. Linking the CESs of Green Cultural Heritage Sites to Restorative Experience*

Little is known about whether CESs, the measurement of the cultural features of an environment, are associated with restorative experiences in green cultural heritage sites. Several restorative experience studies have examined the correlations between perceived sensory dimensions (PSDs, as characterizations of environmental features) and stress reduction achieved through environmental restoration experiences. Grahn and Stigsdotter (2010) identified eight perceptual sensory dimensions of perception and described the people who reported stress as environmentally sensitive to illustrate the relationship between the perceptual sensory dimensions of an urban green space and perceived stress reduction [42]. Luo et al. (2022) investigated the relationship between PSDs and restorative experience in the pavilions of urban parks [16]. Additionally, Memari et al. (2017) investigated the relationship between PSDs and perceived stress reduction using the Short-Revised Restoration Scale, which is based on theoretical interpretations of the SRT [52]. Peschardt and Stigsdotter (2013) examined the experience of attentional restoration in nine small, public urban green spaces in the city of Copenhagen using the perceived restorativeness scale [53]. Therefore, similar to PSDs, as characterizations of environmental features and properties, this study argues that visitors' perceptions of green cultural heritage CESs are potentially linked to restorative experiences.

### *2.4. Hypothesis Development*

Based on the above literature review, the following hypotheses are proposed.

(1) In a GCH site, individuals can feel CES values.
(2) Individuals can perceive stress recovery and attention restoration.
(3) Certain values of CESs can significantly predict recovery potential.

Furthermore, considering the findings of Riechers et al. (2018) on the differences in urban green perception among people with different CES sensitivities [54], we would also like to address the following hypothesis:

(4) In GCH sites, perceived stress reduction and attention recovery differ for individuals with varying CES sensitivity.

Figure 1 illustrates the framework of this study.

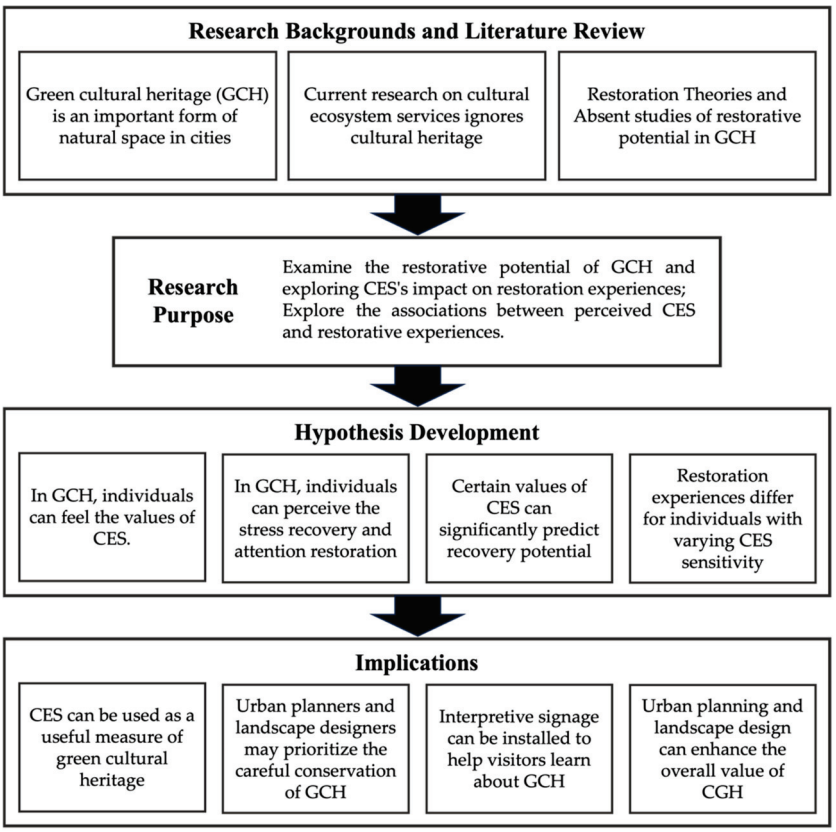



**Figure 1.** The research framework.

## 3. Materials and Methods

### *3.1. Study Site*

Hamarikyu Garden (HG) is a metropolitan garden covering an area of 250,165.81 $m^2$. Located in Chuo Ward, at the mouth of the Sumida River along the Tokyo Bay, HG is the only place in Tokyo that has retained its tidal pond. It is one of only nine places in Japan that have been designated as both a Special National Historic Site of Japan and a Special National Place of Scenic Beauty (Figure 2).

During the Edo period, the garden was used as a residence and falconry ground for the Tokugawa shoguns. After the Meiji Restoration, it was used as a detached palace for the imperial family and was later opened as a public garden in April 1946. In Hamarikyu Garden, there are four water bodies: the tidal pond, two Kamoba (duck-hunting sites), and an inner moat. Around the duck-hunting sites, there are konozoki (small openings) through which nobles would observe the ducks while they were eating and being caught as a traditional form of Japanese entertainment. Around the bay, there are four important buildings, the most famous of which is the Najajima-no-ochaya (teahouse), where visitors can rest for a short time. In addition, there are abundant vegetation spaces, such as three-hundred-year-old pine trees, artificially pruned vegetation, and flower seas. Visitors can experience the rich natural environment and cultural atmosphere (Figure 3).

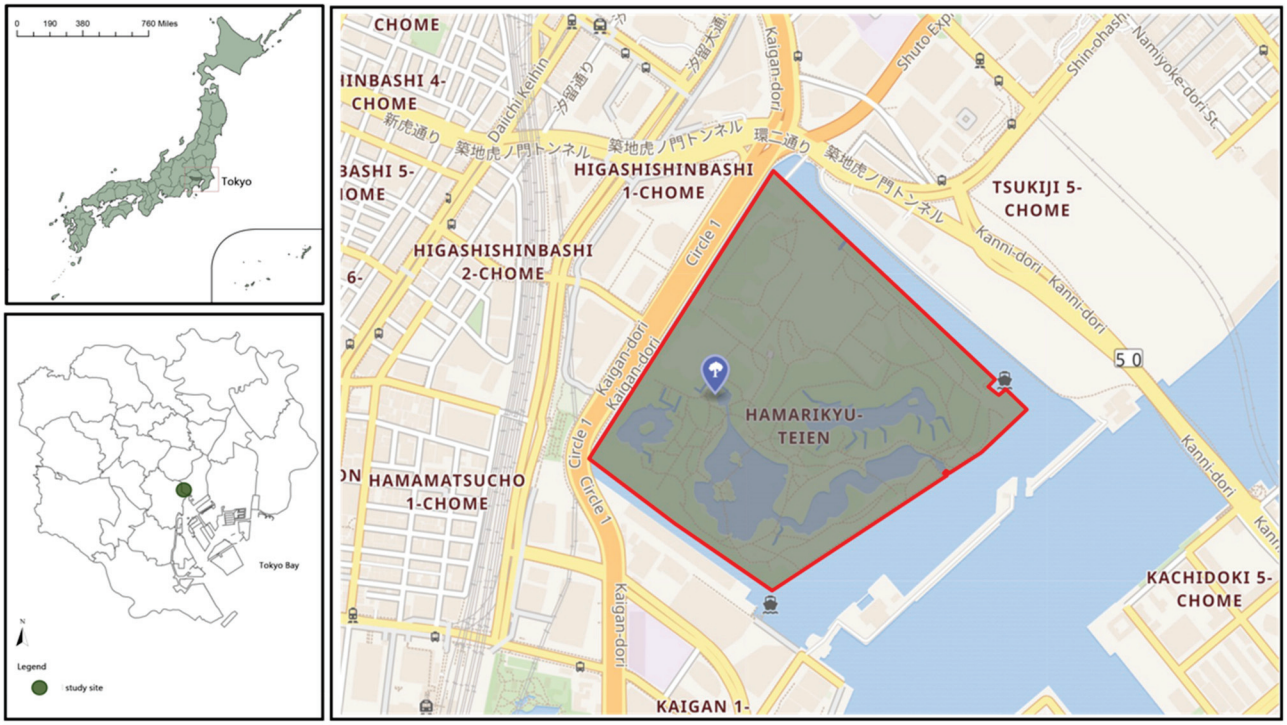



**Figure 2.** Location of the study site (map credit: OpenStreetMap).

**Figure 3.** Locations of on-site natural images ((**N1**) the inner moat, (**N2**) an open space, and (**N3**) the tidal pond) and cultural images ((**C1**) konozoki, (**C2**) the bridge over the pond, and (**C3**) the teahouse) of HG (map credit: Google Maps).

### *3.2. Participants and Procedures*

First, a pilot survey was conducted in September 2022. Six research assistants participated in the pilot survey, after which they became volunteers to guide survey subjects on tours. After the pilot survey and training, these volunteers were very familiar with the experimental sites and processes. The formal on-site survey was conducted in October, and a total of 64 students were recruited as a sample through web announcements and posters at Chiba University. The final version of the survey questionnaire was completed after considering the feedback of the six pilot survey respondents. The final sample included 24 males and 40 females, ranging from 22 to 40 years of age (mean age: 25.8 ± 3.51 years). In terms of their educational background, 26.56% were undergraduate students, 50.00%

were graduate students, and 23.44% were doctoral students. All students were from the Graduate School of Horticulture, majoring in landscape architecture, urban planning, and other majors (environmental science for bioproduction, applied biological chemistry, food and resource economics, etc.).

The formal on-site survey took approximately 2.5 h to complete (Figure 4). It required subjects (groups of one to three people) to first tour the garden for approximately two hours to ensure that they had a sufficient perception of it. Additionally, to ensure that the respondents visited most of the main tour areas of the gardens and experienced similar levels of green cultural heritage environments (cultural, historical, and natural), each group was guided by a research assistant. In addition, during the tour, the research assistants did not make any introductions to the garden to avoid any disruption to the respondents' experiences. Subjects were also forbidden to communicate or interact with each other. After the tour, they completed the questionnaire in a quiet pavilion to prevent their responses from being influenced by external factors. This study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of Chiba University. However, there was no examination of the human body or physiological data in this study, and all participants were kept anonymous. Therefore, no ethics review was required to be submitted to the ethics committee. All participants signed an informed consent form.

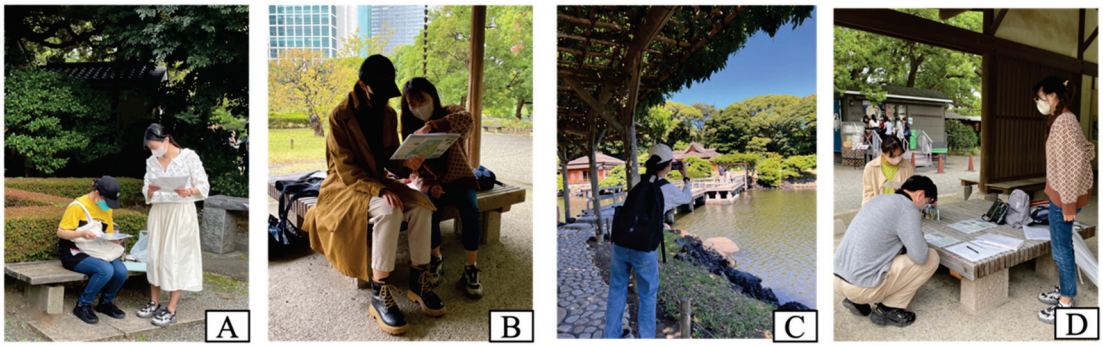



**Figure 4.** The survey procedure. (**A**) Get the brochure of the GCH and go to the pavilion near the entrance; (**B**) Read the brochure and start their tour with a volunteer who would guide the route; (**C**) Take a two-hour tour according to the route; (**D**) Go back to the pavilion to complete the questionnaire after a short break.

### *3.3. Measures*

The categories used for the CES values were originally adapted from the types of CESs described in the MA. The number of CES values and the specific indicators constantly change depending on the object and purpose of the study [17,55,56]. To assist with the contextualization and appropriate classification of the CESs, the authors (eight, comprising one professor, one assistant professor, and six Ph.D. students) visited Hamarikyu Garden in June 2022 to gain a comprehensive understanding of the garden's physical surroundings, historical elements, and cultural characteristics. Finally, following Sherrouse et al. (2014) [57], van Riper et al. (2020) [58], and Zhang et al. (2022) [17], after fieldwork and a discussion of the prior literature, the authors screened and identified ten CES dimensions: aesthetics, recreation, social relations, education, nature appreciation, sense of place, bequest, health, therapeutics, and cultural heritage (Table 1). The CESs were all measured using a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree).

**Table 1.** Classification categories of CESs.

| CES Values | Description |
|---|---|
| Aesthetics | I think this place has an attractive landscape. |
| Recreation | I think there are opportunities for recreation in this place. |
| Social relations | I can spend time with family, friends, or other people here. |
| Education | I think this place can provide opportunities for scientific research or public education. |
| Nature appreciation | I think this place has a variety of animals, plants, and other living species. |
| Sense of place | I feel a sense of belonging through some certain features here. |
| Bequest | I think this place is likely to be passed down unchanged for generations to come. |
| Health | I think this place makes me feel better physically. |
| Therapeutics | I think this place makes me forget my troubles and helps me feel relaxed. |
| Cultural heritage | I think this place has several historically or culturally significant landscape features. |

Two psychological scales were used to measure the participants' self-reported stress reduction and directed attention restoration outcomes. All outcomes were measured using a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree). The participants were first asked about their perceived restoration in terms of "restorative experiences", "positive emotions", and "stress reduction" [45,59]. While being away is one of the components of the ART concept, along with fascination, extent, and compatibility [60], it is more reasonable to use physical components (novelty) and psychological components (escape) instead of the single factor of being away [61]. Thus, the improved perceived attention restoration scale consists of five factors: fascination, novelty, escape, extent, and compatibility. Each factor has three to five items (Table 2).

**Table 2.** Seven-point scale of perceived stress reduction and perceived attention restoration.

| Measurement | Restorative Experiences | Reference |
|---|---|---|
| Stress reduction | I forget daily worries and feel restored here.<br>I feel happy and comfortable here.<br>I feel relaxed and calm here. | [45,59] |
| Novelty | This is an escape from everyday surroundings.<br>I can switch up my daily activities (study/work) here.<br>There are many novelties here. | [60–62] |
| Escape | Being here makes me feels like an escape from my daily chores.<br>This place takes my mind off the daily tasks I must do for a while.<br>This is a place where I can forget the presence of others and enjoy being alone.<br>I feel liberated from my everyday surroundings here. | |
| Fascination | The environment has a charming quality.<br>My attention was drawn to many interesting things.<br>I want to get to know this place better.<br>There is so much to explore and discover here.<br>I want to spend more time looking around this place. | |
| Extent | There are so many troubling things going on here.<br>It is a confusing place to be.<br>There are many distractions here.<br>It is very disorganized here. | |
| Compatibility | I can do what I like here.<br>I feel a sense of belonging here.<br>I feel that I can fit in with this environment.<br>Staying in this place suits my personality.<br>I can find many ways to enjoy the surroundings. | |

### *3.4. Analysis*

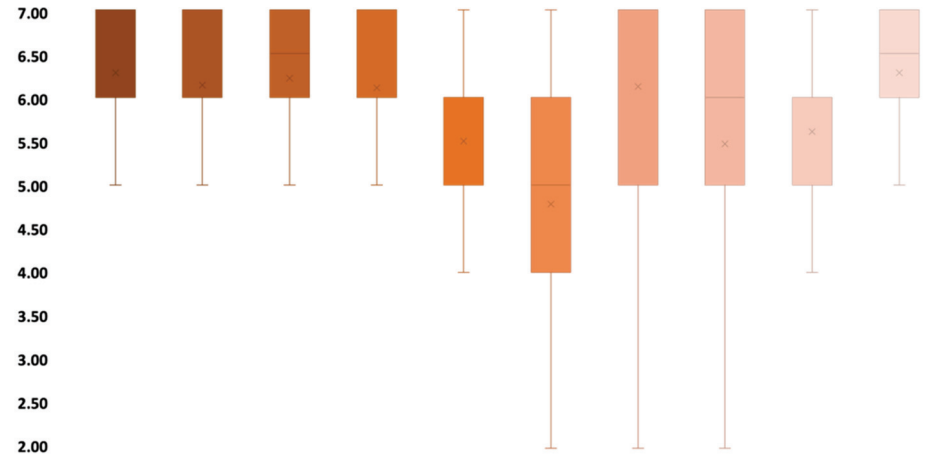
This study utilized a within-group design. The survey data were compiled and statistically analyzed using Excel software (Version 16.76). All statistical analyses were performed

using JASP 0.16.4, and the level of significance was set at $p < 0.05$. First, the reliability (internal consistency) of the scales was assessed and measured using Cronbach's alpha index; the validity of the two psychological scales were measured using Kaiser–Meyer–Olkin values. Then, simple linear regression analyses were used to examine the linear relationships between restorative experience outcomes and ten CES items. Afterwards, a multiple linear regression analysis (introduced via the method "Enter") was used to explore the CES predictors that significantly affect perceived stress reduction and attention restoration. The independent variables of the above two models were the ten CES factors, and the dependent variables were the perceived stress reduction, overall perceived attention restoration, and five components of the perceived attention restoration. Additionally, based on the degree of the CES values, visitors were divided into two categories in the following analysis: a sensitive group (CES values higher than the mean value) and an insensitive group (CES values lower than or equal to the mean value). An independent samples *t*-test was used to determine the differences in perceived stress reduction and attention restoration between the two groups.

## 4. Results

### *4.1. Assessment of the CES Values and the Perception of Stress Reduction and Attention Restoration*

As shown in Figure 5, the 10 CES values of HG were rated highly. All mean values were greater than five points except for sense of place (4.78 ± 1.18). Aesthetics (6.28 ± 1.10), cultural heritage (6.28 ± 0.86), social relations (6.22 ± 0.96), recreation (6.14 ± 0.98), bequest (6.13 ± 1.15), and educational values (6.11 ± 0.97) had mean values greater than six, indicating that they were perceived to the highest degree. These were followed by therapeutics (5.61 ± 1.21), nature appreciation (5.50 ± 1.15), and health (5.47 ± 1.31).




| | Aesthetics | Recreation | Social relations | Education | Nature appreciation | Sense of place | Bequest | Health | Therapeutics | Cultural heritage |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 6.28 | 6.14 | 6.22 | 6.11 | 5.50 | 4.78 | 6.13 | 5.47 | 5.61 | 6.28 |
| SD | 1.10 | 0.98 | 0.96 | 0.97 | 1.15 | 1.18 | 1.15 | 1.31 | 1.21 | 0.86 |

**Figure 5.** Overall assessment of CES values (means ± standard deviations).

For perceived attention restoration, most respondents perceived a high level of attention restoration when they stayed in the green cultural heritage area; the mean score was greater than five except for compatibility (4.64 ± 1.03) (Figure 6). In detail, extent (5.69 ± 0.81) received the highest score, indicating that HG allowed subjects to perceive a high range of exploration and a coherent environment. Extent was followed by fascination (5.43 ± 0.85), which indicates that green cultural heritage can provoke effortless attention from respondents. Escape (5.22 ± 1.15) indicated that the respondents believed that staying in such an environment could make them feel disconnected from their daily work environment. Compatibility (4.64 ± 1.03) received the lowest rating, indicating that the respondents had difficulty matching their internal motivations with the environment.

In addition, the perceived stress reduction (5.83 ± 0.82) was greater than the mean of each component of attention restoration, indicating that the visitors felt a greater reduction in stress in the HG.

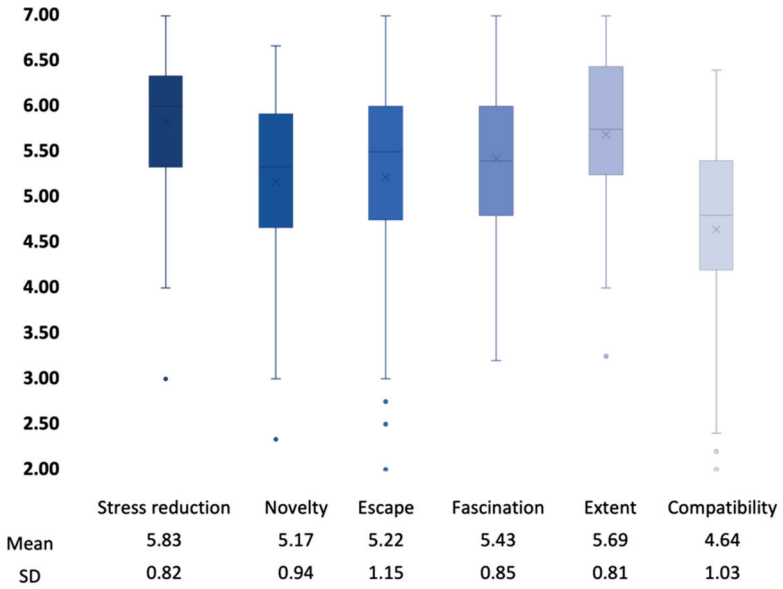



**Figure 6.** Overall assessment of perceived attention restoration components and perceived stress reduction (mean ± standard deviations).

The reliability of the CESs, perceived stress reduction, and attention restoration was verified, and Cronbach's alpha ranged from 0.616 to 0.891; the results showed high internal consistency (Table A1). Moreover, the Kaiser–Meyer–Olkin value for the perceived stress reduction scale was 0.707 ($p < 0.001$) and its value for the perceived attention restoration scale was 0.717 ($p < 0.001$), indicating that the above two psychological scales demonstrated high validity.

### *4.2. Association of CES Values with Perceived Stress Reduction and Components of Perceived Attention Restoration*

The results for each CES from our linear regression analysis are shown in Table 3, arranged into one section for perceived stress reduction and another for each component of perceived attention restoration.

**Table 3.** Estimates and statistics of the CESs' effect on perceived stress reduction, novelty, escape, fascination, extent, and compatibility.

| | B | St. Error | Sig. | 95% Confidence Interval | | F | $R^2$ |
|---|---|---|---|---|---|---|---|
| | | | | Lower | Upper | | |
| *Perceived Stress reduction* | | | | | | | |
| Aesthetics | 0.455 | 0.070 | <0.001 | 0.366 | 0.642 | 53.300 | 0.462 |
| Recreation | 0.490 | 0.085 | <0.001 | 0.321 | 0.659 | 33.460 | 0.351 |
| Social relations | 0.533 | 0.083 | <0.001 | 0.366 | 0.700 | 40.754 | 0.397 |
| Education | 0.164 | 0.133 | 0.222 | −0.102 | 0.431 | 1.519 | 0.024 |
| Nature appreciation | 0.204 | 0.086 | 0.021 | 0.032 | 0.377 | 5.620 | 0.083 |
| Sense of place | 0.284 | 0.080 | <0.001 | 0.124 | 0.443 | 12.669 | 0.170 |
| Bequest | 0.216 | 0.085 | 0.014 | 0.046 | 0.387 | 6.434 | 0.094 |
| Health | 0.117 | 0.077 | 0.136 | −0.038 | 0.251 | 0.271 | 0.035 |
| Therapeutics | 0.262 | 0.079 | 0.002 | 0.104 | 0.419 | 11.037 | 0.151 |
| Cultural heritage | 0.449 | 0.106 | <0.001 | 0.237 | 0.661 | 17.916 | 0.224 |

**Table 3.** *Cont.*

| | B | St. Error | Sig. | 95% Confidence Interval | | F | $R^2$ |
|---|---|---|---|---|---|---|---|
| | | | | Lower | Upper | | |
| *Novelty* | | | | | | | |
| Aesthetics | 0.530 | 0.093 | <0.001 | 0.270 | 0.640 | 24.163 | 0.280 |
| Recreation | 0.430 | 0.110 | <0.001 | 0.193 | 0.633 | 14.085 | 0.185 |
| Social relations | 0.245 | 0.108 | <0.001 | 0.269 | 0.703 | 20.114 | 0.245 |
| Education | 0.339 | 0.116 | 0.006 | 0.097 | 0.561 | 8.037 | 0.115 |
| Nature appreciation | 0.198 | 0.102 | 0.117 | −0.042 | 0.368 | 2.533 | 0.039 |
| Sense of place | 0.328 | 0.096 | 0.008 | 0.070 | 0.454 | 7.465 | 0.107 |
| Bequest | 0.235 | 0.101 | 0.062 | −0.010 | 0.394 | 3.616 | 0.055 |
| Health | 0.017 | 0.091 | 0.894 | −0.170 | 0.195 | 0.018 | 0.000 |
| Therapeutics | 0.195 | 0.097 | 0.123 | −0.042 | 0,346 | 2.441 | 0.038 |
| Cultural heritage | 0.316 | 0.133 | 0.011 | 0.083 | 0.613 | 6.900 | 0.100 |
| *Escape* | | | | | | | |
| Aesthetics | 0.511 | 0.114 | <0.001 | 0.306 | 0.762 | 21.864 | 0.261 |
| Recreation | 0.507 | 0.128 | <0.001 | 0.336 | 0.847 | 21.463 | 0.257 |
| Social relations | 0.500 | 0.131 | <0.001 | 0.334 | 0.860 | 20.657 | 0.250 |
| Education | 0.224 | 0.146 | 0.075 | −0.027 | 0.557 | 3.288 | 0.050 |
| Nature appreciation | 0.271 | 0.122 | 0.030 | 0.026 | 0.515 | 4.904 | 0.073 |
| Sense of place | 0.460 | 0.110 | <0.001 | 0.229 | 0.667 | 16.681 | 0.212 |
| Bequest | 0.207 | 0.124 | 0.101 | −0.041 | 0.453 | 2.776 | 0.043 |
| Health | 0.140 | 0.110 | 0.271 | −0.098 | 0.342 | 1.236 | 0.020 |
| Therapeutics | 0.502 | 0.104 | <0.001 | 0.269 | 0.685 | 20.922 | 0.252 |
| Cultural heritage | 0.188 | 0.167 | 0.137 | −0.082 | 0.585 | 2.273 | 0.035 |
| *Fascination* | | | | | | | |
| Aesthetics | 0.491 | 0.086 | <0.001 | 0.209 | 0.552 | 19.670 | 0.241 |
| Recreation | 0.530 | 0.093 | <0.001 | 0.273 | 0.646 | 24.239 | 0.281 |
| Social relations | 0.467 | 0.100 | <0.001 | 0.215 | 0.613 | 17.309 | 0.218 |
| Education | 0.375 | 0.103 | 0.002 | 0.122 | 0.535 | 10.143 | 0.141 |
| Nature appreciation | 0.380 | 0.087 | 0.002 | 0.108 | 0.457 | 10.463 | 0.144 |
| Sense of place | 0.271 | 0.088 | 0.030 | 0.019 | 0.372 | 4.915 | 0.073 |
| Bequest | 0.411 | 0.085 | <0.001 | 0.132 | 0.474 | 12.589 | 0.169 |
| Health | 0.002 | 0.082 | 0.986 | −0.163 | 0.166 | 0.000 | 0.000 |
| Therapeutics | 0.335 | 0.084 | 0.004 | 0.083 | 0.417 | 8.920 | 0.126 |
| Cultural heritage | 0.491 | 0.110 | <0.001 | 0.268 | 0.707 | 19.700 | 0.241 |
| *Extent* | | | | | | | |
| Aesthetics | 0.291 | 0.090 | 0.020 | 0.036 | 0.395 | 5.732 | 0.085 |
| Recreation | 0.256 | 0.101 | 0.042 | 0.008 | 0.414 | 4.332 | 0.065 |
| Social relations | 0.308 | 0.102 | 0.013 | 0.056 | 0.464 | 6.479 | 0.095 |
| Education | 0.127 | 0.105 | 0.316 | −0.104 | 0.317 | 1.021 | 0.016 |
| Nature appreciation | 0.271 | 0.087 | 0.030 | 0.019 | 0.365 | 4.921 | 0.074 |
| Sense of place | 0.363 | 0.081 | 0.003 | 0.087 | 0.412 | 9.380 | 0.131 |
| Bequest | −0.013 | 0.089 | 0.918 | −0.188 | 0.169 | 0.011 | 0.000 |
| Health | 0.338 | 0.074 | 0.006 | 0.061 | 0.357 | 8.008 | 0.114 |
| Therapeutics | 0.160 | 0.084 | 0.206 | −0.061 | 0.276 | 1.633 | 0.026 |
| Cultural heritage | 0.277 | 0.116 | 0.027 | 0.031 | 0.493 | 5.146 | 0.077 |
| *Compatibility* | | | | | | | |
| Aesthetics | 0.448 | 0.107 | <0.001 | 0.208 | 0.635 | 15.590 | 0.201 |
| Recreation | 0.377 | 0.123 | 0.002 | 0.149 | 0.642 | 10.260 | 0.142 |
| Social relations | 0.316 | 0.129 | 0.011 | 0.080 | 0.598 | 6.869 | 0.100 |
| Education | 0.155 | 0.133 | 0.222 | −0.102 | 0.431 | 1.519 | 0.024 |
| Nature appreciation | 0.392 | 0.105 | 0.001 | 0.142 | 0.562 | 11.241 | 0.153 |
| Sense of place | 0.448 | 0.099 | <0.001 | 0.193 | 0.590 | 15.550 | 0.201 |
| Bequest | 0.016 | 0.114 | 0.897 | −0.212 | 0.242 | 0.017 | 0.000 |
| Health | 0.066 | 0.100 | 0.605 | −0.147 | 0.251 | 0.270 | 0.004 |
| Therapeutics | 0.252 | 0.105 | 0.044 | 0.006 | 0.425 | 4.220 | 0.064 |
| Cultural heritage | 0.245 | 0.148 | 0.051 | −0.002 | 0.590 | 3.944 | 0.060 |

Note: The results show the 10 simple linear regression analyses for evaluating mental restoration, and the bold numbers indicate the CESs significantly associated with perceived stress reduction and components of perceived attention restoration.

For perceived stress reduction, aesthetics (B = 0.455, $p < 0.001$), recreation (B = 0.490, $p < 0.001$), social relations (B = 0.533, $p < 0.001$), cultural heritage (B = 0.449, $p < 0.001$), nature appreciation (B = 0.204, $p = 0.021$), bequest (B = 0.216, $p = 0.014$), and therapeutics (B = 0.262, $p = 0.002$) could significantly help people feel psychologically relaxed and recover from daily stress.

For components of perceived attention restoration, the CESs that significantly impacted novelty were aesthetics (B = 0.455, $p < 0.001$), recreation (B = 0.430, $p < 0.001$), sense of place (B = 0.328, $p = 0.008$), education (B = 0.339, $p = 0.006$), cultural heritage (B = 0.316, $p = 0.011$), and social relations (B = 0.245, $p < 0.001$). This means that HG brought beautiful landscapes, sounds, and smells to the respondents and provided them with a place to spend time outdoors. In addition, the participants' experiences in HG also allowed them to discover and feel a historical and cultural atmosphere.

For escape, the six CES values of aesthetics (B = 0.511, $p < 0.001$), recreation (B = 0.507, $p < 0.001$), social relations (B = 0.500, $p < 0.001$), therapeutics (B = 0.502, $p < 0.001$), nature appreciation (B = 0.271, $p = 0.03$), and sense of place (B = 0.460, $p < 0.001$) contributed to the respondents' significant feelings of being away from their daily environment, including work.

Fascination indicates the attractiveness of an environment, which motivates respondents to explore environmental spaces. According to the results, all nine CES values significantly ($p < 0.05$) influenced the perception of fascination except for health (B = 0.002, $p = 0.986$), which is related to physical exercise. Fascination is related to the attractiveness of the environment, so this result suggests that the higher an individual's perception of the nine CES values, the higher their level of fascination with the GCH as well.

Extent represents the environments with the potential for continued exploration [46,63,64]. The results indicate that sense of place (B = 0.363, $p = 0.003$), social relations (B = 0.308, $p = 0.013$), health (B = 0.338, $p = 0.006$), cultural heritage (B = 0.277, $p = 0.027$), nature appreciation (B = 0.271, $p = 0.030$), aesthetics (B = 0.291, $p = 0.020$), and recreation (B = 0.256, $p = 0.042$) were all significantly associated with extent. Hence, the participants were more likely to explore environments that had a sense of place. Moreover, they were more attracted to spaces where they could engage in social and healthy activities.

Compatibility represents the ability of a place to provide opportunities to engage in activities that are "compatible" with internal motivations. In HG, perceptions of aesthetics (B = 0.448, $p < 0.001$), sense of place (B = 0.448, $p < 0.001$), nature appreciation (B = 0.392, $p = 0.001$), recreation (B = 0.377, $p = 0.002$), social relations (B = 0.316, $p = 0.011$), and therapeutics (B = 0.252, $p = 0.044$) were all significantly correlated with compatibility.

### *4.3. CES Items That Significantly Predict Perceived Stress Reduction and Attention Restoration*

Seven multiple linear regressions were conducted to establish the overall relationship between the ten CES values of green cultural heritage and attention recovery and stress reduction. The dependent variables of the seven regression models were perceived stress reduction, overall perceived attention restoration, and five components of attention restoration. The normality of the model residuals (Table 4) was tested using the Kolmogorov–Smirnov test, and the results showed normal distribution ($p > 0.05$).

**Table 4.** Kolmogorov–Smirnov test results.

| | PSR | PAR | Novelty | Escape | Fascination | Extent | Compatibility |
|---|---|---|---|---|---|---|---|
| K-S Z value | 0.146 | 0.134 | 0.132 | 0.167 | 0.065 | 0.884 | 0.104 |
| *p* value | 0.129 | 0.188 | 0.218 | 0.056 | 0.950 | 0.415 | 0.493 |

PSR: perceived stress reduction; PAR: perceived attention restoration.

Arriaza et al. (2004) stated that a model's tolerance value < 0.2 or VIF value > 10 indicates a multicollinearity problem [65]. The current model did not find a multicollinearity problem and was considered acceptable, with the lowest tolerance = 0.476 and the highest VIF = 2.099 (Table 5).

**Table 5.** Significant predictors of perceived stress reduction, perceived attention restoration, and components of perceived attention restoration.

| Dependent Variable | Independent Variable | Unstandardized Beta | Standard Error | Standardized Beta | t | Sig. | Collinearity Statistics | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Tolerance | VIF |
| Perceived stress reduction (adjusted $R^2$ = 0.639) | (constant) | 0.422 | 0.663 | | 0.637 | 0.527 | | |
| | Aesthetics | 0.283 | 0.080 | 0.381 | 3.554 | <0.001 | 0.591 | 1.691 |
| | Cultural heritage | 0.183 | 0.091 | 0.192 | 2.002 | 0.050 | 0.737 | 1.357 |
| Perceived attention restoration (adjusted $R^2$ = 0.598) | (constant) | 0.969 | 0.537 | | 1.803 | 0.077 | | |
| | Aesthetics | 0.219 | 0.064 | 0.353 | 3.399 | 0.001 | 0.591 | 1.691 |
| | Sense of place | 0.173 | 0.055 | 0.300 | 3.120 | 0.003 | 0.692 | 1.445 |
| Novelty (adjusted $R^2$ = 0.303) | (constant) | 0.839 | 0.980 | | 0.856 | 0.396 | | |
| | Aesthetics | 0.281 | 0.118 | 0.327 | 2.388 | 0.021 | 0.591 | 1.691 |
| Escape (adjusted $R^2$ = 0.403) | (constant) | 0.077 | 1.103 | | 0.070 | 0.944 | | |
| | Aesthetics | 0.286 | 0.132 | 0.274 | 2.165 | 0.035 | 0.591 | 1.691 |
| | Sense of place | 0.262 | 0.115 | 0.270 | 2.306 | 0.025 | 0.692 | 1.445 |
| | Therapeutics | 0.295 | 0.134 | 0.311 | 2.203 | 0.032 | 0.476 | 2.099 |
| Fascination (adjusted $R^2$ = 0.420) | (constant) | 0.206 | 0.807 | | 0.256 | 0.799 | | |
| | Cultural heritage | 0.274 | 0.111 | 0.276 | 2.469 | 0.017 | 0.737 | 1.357 |
| Compatibility (adjusted $R^2$ = 0.292) | (constant) | 1.018 | 1.080 | | 0.943 | 0.350 | | |
| | Aesthetics | 0.309 | 0.130 | 0.329 | 2.387 | 0.021 | 0.591 | 1.691 |
| | Sense of place | 0.256 | 0.111 | 0.292 | 2.295 | 0.026 | 0.692 | 1.445 |

Note: No CES item was a significant predictor of extent, so this component was omitted.

As shown in Table 5, in terms of stress recovery, the values of aesthetic (B = 0.283, $p < 0.001$) and cultural heritage (B = 0.183, $p = 0.05$) were able to significantly influence stress recovery, with these two factors explaining 63.9% of the variance. In terms of attention recovery, aesthetics (B = 0.219, $p = 0.001$) and sense of place (B = 0.173, $p = 0.003$) positively influenced attention restoration, with the two explaining 59.8% of the variance. This result suggests that the higher the level of perceived environmental aesthetics among green cultural heritage sites, the greater the perceived restoration of attention and stress relief. Furthermore, attention to the historical atmosphere of the site was effective at reducing stress, and a higher sense of connection to the site significantly increased participants' levels of attention.

### *4.4. Differences in Perceived Stress Reduction and Attention Restoration among People with Different CES Sensitivities*

By calculating the mean value of the ten CESs assessed by all respondents ($M_{CES}$ = 5.85), the participants were divided into a sensitive group (sensitive to CES perception (mean > 5.85)) and an insensitive group (not sensitive to CES perception (mean $\leq$ 5.85)). The Mann–Whitney U-test was performed to explore whether there was a significant difference between the perceived mental restoration of the two groups (Figure 7). Attention recovery was significantly lower in the insensitive group (4.763 $\pm$ 0.672) than in the sensitive group (5.571 $\pm$ 0.462) ($p < 0.001$). In addition, perceived stress reduction was lower in the insensitive group (5.271 $\pm$ 0.832) than in the sensitive group (6.234 $\pm$ 0.521) ($p < 0.001$).

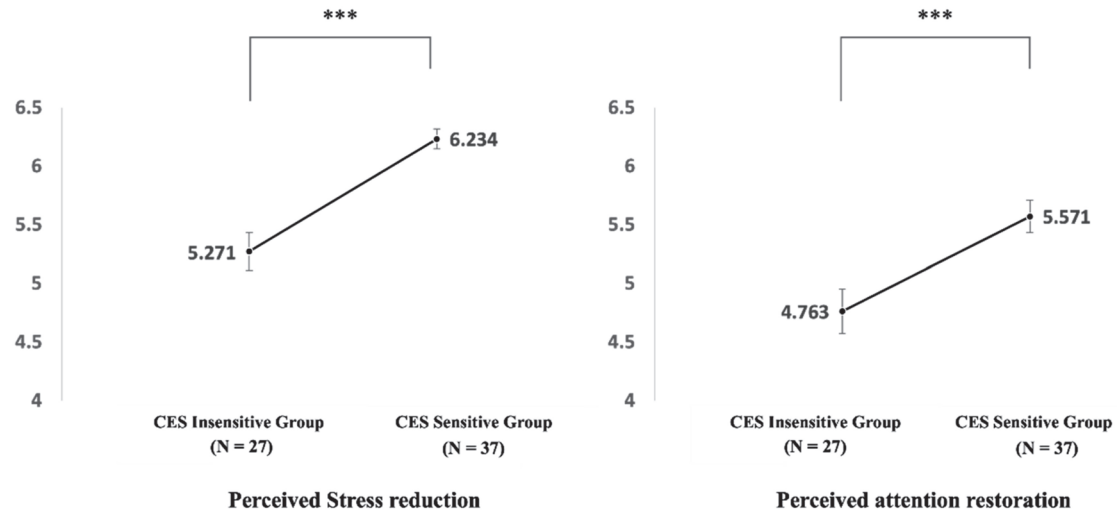



**Figure 7.** Differences in restorative experiences between the sensitive and insensitive groups (*** $p < 0.001$).

## 5. Discussion

Based on an onsite questionnaire distributed to green cultural heritage users in Hamarikyu Garden, this paper explores the values of CESs in a green cultural heritage site and the relationship between cultural ecosystem values and perceived attention restoration/stress recovery. The main results are as follows: (1) all nine cultural ecosystem values of green cultural heritage except for sense of place received high ratings, especially the values aesthetic, cultural heritage, social relations, recreation, bequest, and education; (2) most of the CES values are associated with perceived stress reduction and the components of perceived attention restoration, respectively; (3) the values of aesthetics and cultural heritage significantly affected stress restoration, while attention restoration showed a significant positive correlation with the aesthetic and sense of place values; and (4) the more visitors perceived the CES values, the more significant their perceived stress reduction and attention recovery were. Both expected and unexpected results were found. The possible explanations are discussed below.

### *5.1. Representation of CES Values in Green Cultural Heritage*

Compared to other green spaces such as parks, greenways, and forests in the city, green cultural heritage sites have more intangible historical, cultural, educational, and even legacy value. For example, there are many very Japanese landscape expressions, such as traditional tea house buildings, shrines, konozoki (small openings), a bridge over the pond, the pond, open space, water gates, pine trees, and red leaves at the study site (Figure 3). These landscape elements create a scene that combines Japanese history and culture, allowing people to feel high levels of some CES values such as the historical and cultural dimensions. Surprisingly, however, the overall rating for sense of place was low, perhaps due to the fact that the chosen site is a setting of an environment dominated by natural elements and historical elements that are very different from the daily urban environment in which the students live (modern and human-made). According to the results of Section 3.1, our findings support the argument that green cultural heritage provides multiple interactive benefits. In general, all CES values were considered quite important, especially in terms of aesthetics, social relations, recreation, bequest, cultural heritage, and educational values.

It should be noticed that aesthetic and social values are always considered to be very important in green spaces. Specifically, in a survey of a large sample of Berlin city dwellers, aesthetic and social relation values were considered the most important CESs in urban green spaces, which is similar to our findings [54].

Recreation is one of the numerous benefits that individuals and societies gain from landscapes [66]. Compared to other findings, the experiential value provided by greenways has been emphasized in studies of urban greenways, highlighting the importance of recreational connections [28]; similarly, Beckmann-Wübbelt et al. (2021) reported that recreational values were the most desired in forests [67], which is consistent with our findings.

However, bequest, cultural heritage, and educational values are unique compared to other studies which focused on other types of green spaces. For example, in a study by Zhang et al. (2022), bequest did not score very high, even in urban parks with historical and cultural features [17]. Cultural heritage values were considered the least important [28,54]. In addition, cultural heritage and educational values were scored the lowest in forests according to Beckmann-Wübbelt et al. (2021) [67]. These results from previous studies contradict our findings. Green cultural heritage itself is a combination of natural and cultural heritage as it represents the association of humans and nature as an equal community and is considered an organically formed cultural landscapes [14]. Bučas (2006) argued that purposefully formed cultural landscapes give meaning to the results of a person's prioritized activities and show the supremacy of humanity's creative activity over nature [14].

Hence, we can see that the CES values represented in green cultural heritage are not only the regular values which scored very high in other green spaces, such as aesthetics, social relations, recreation, but also some unique values such as bequest, cultural heritage, and educational value.

### *5.2. Driving Factors for the Restorative Experience of Green Cultural Heritage*

Restoration theories are usually related to perceived environmental safety [68], attractiveness [43], sensory dimensions, and preferences [53,69]. However, this study considered the drivers of recovery from the perspective of perceived cultural ecosystem services. Our results (Table 5) suggest that aesthetic and cultural heritage values are significant predictors of stress reduction; aesthetics and sense of place significantly influence attention restoration.

Aesthetic appreciation is an important factor for people to feel restored in green spaces [60,70,71]. In line with the results of previous studies [16,72,73], the present study suggests the importance of aesthetic value as an indicator of stress and attention recovery. Consistent with Kaplan (1995) [40], the aesthetic quality of a landscape can act as a soft charm that contributes to recovery from directed attention fatigue; attention restoration, escape, compatibility, and novelty were positively correlated with aesthetic value (Table 5). Therefore, we suggest that methods used to improve aesthetic value can be used to improve the restoration quality.

Cultural heritage values are predictors of stress reduction. This result is consistent with previous research findings [49,59] that historical and cultural values have the potential to offer visitors a restorative experience that provides respite from the stress of daily life. Additionally, as shown in Table 5, they are also important indicators of feelings of fascination. Masullo et al. (2021) found that the dimension most influenced by the component aspects of history and culture is fascination [74]. Therefore, preserving and enhancing the value of cultural heritage is a key proposition in the future of green cultural heritage.

Sense of place is also a reliable predictor of attention recovery potential. Ulrich (1983) asserted the role of memory in cognitive and affective assessments of natural environments and hypothesized a relationship between recovery potential and positive past experiences crystallized in memory [75]. Such memories of positively valanced content have been shown to alleviate negative emotions [76]. Ratcliffe and Korpela (2016) argued that the extent to which people consider a place to be part of themselves and more desirable than any other place for their purpose can be an emotional perception of cognition and indicate potential for recovery and restoration [77].

Thus, the value of being able to bring fond memories or have self-identity within a sense of place can be valuable in the design and management of the physical environments of restorative spaces.

### 5.3. More Perception of CESs Leads to a Better Restorative Experience

Similar to the findings of Riechers et al. (2018) [54], who found differences in the experience results of urban green among people with different CES sensitivities, our results found that people with different sensitivities in perceiving the CES values also produced significant differences in restorative experiences (Figure 7). In other words, people's levels of perception of CESs influence the extent of their self-reported mental recovery (e.g., perceived stress reduction, perceived attention restoration). Previous restorative-related studies have often emphasized that certain landscape elements [15] or their proportions [78] lead to restoration, ignoring the environmental characteristics formed by the elements as a whole. CESs refer to the non-material benefits that people obtain from ecosystems, and they have direct influences on the quality of an individual's life [20]. Our study examined ten CES dimensions in GCH: aesthetics, recreation, social relations, education, nature appreciation, sense of place, bequest, health, therapeutics, and cultural heritage. Thus, the average value of the ten CES dimensions, as an individual's overall perception of the non-material benefits (natural, cultural, historical, educational, etc.) received from a given ecosystem, was used to explore the differences in restorative experiences between populations with different levels of CES perception. As can be seen from Table 4 (regression analysis results), we found that the CES values of aesthetics, cultural heritage, sense of place, and therapeutics all have a significant impact on restorative experience. The mechanisms through which these indicators drive mental restoration were discussed in the previous subsection. Moreover, other studies found that entertainment [79], nature appreciation [46], education [80], and health value [81] will affect people's restorative experience in an environment to a certain extent. Nawrath et al. (2022) found that cultural background affects individuals' experience of green spaces as a source of attention restoration and stress reduction effects [82]. Additionally, studies have been conducted in which people perceive different strengths of attraction with different perceived species richness. Perceiving richer species diversity was found to facilitate recovery from stress [83]. Therefore, in summary, these findings may explain why the higher an individual's overall perceived CES value, the higher their quality of self-reported mental restoration is. This differential perception of mental recovery may be an important means of answering the question of how to construct more restorative environments.

## 6. Conclusions

Although a number of studies have pointed to the benefits of natural environments or historical elements for the quality of people's perceived restoration, green cultural heritage has been neglected for a long time. As a natural public space in the city, the value of a green cultural heritage site lies in its offering of a long-term historical view, questioning its role in people's memory and identity. However, a green cultural heritage site also has an important heritage value that lies precisely in its nature as a humanized and living space, that is, providing a place for relaxation and recovery from mental fatigue.

Few CES studies have addressed cultural heritage. The results of this study suggest that green cultural heritage has the attributes of cultural heritage, education, and bequest. Aesthetic and cultural heritage significantly affect perceived stress reduction, while attention recovery shows a significant positive relationship with aesthetic value and sense of place. The more visitors perceive the value of CESs, the more significant the perceived stress reduction and attention recovery will be. Thus, the value of CESs can be related to perceived psychological recovery in green cultural heritage. Through an objective description of potential health-promoting qualities, our findings can be utilized as inspiration for designing natural restorative environments. Furthermore, our results demonstrate the reliability and validity of using CESs for evaluating the environmental characteristics of green cultural heritage sites. Their application in future cultural heritage research should be encouraged.

The research implications of this study are as follows. First, CESs can be used as useful measures of green cultural heritage. Scholars did not to adequately mention the value

of culture and history among perceptual factors in previous assessments of perceptions of green space. Nolin (2019) argued that in the Anthropocene era, any natural place has cultural value because it has a human imprint, especially in urban environments [84]. Regarding the cultural dimension of PSDs, Peschardt and Stigsdotter (2013) described it as an environment with cultural characteristics such as fountains, sculptures, or exotic plants [53], while Luo et al. (2022) described it as having many human-made elements [16]. The experience of human-fashioned, human-made components, such as fountains, statues, and canals, are referred to as culturally relevant elements [85] and inherent physical relics. In contrast to the simple cultural dimension, cultural heritage is a tangible and intangible asset passed down through the generations [1]. It emphasizes not only the inherent temporal dimension of all physical remains but also the role of heritage as a source of historical knowledge, which people in different periods have used as a tool to learn more about the ways of life of previous generations [86]. The three values of cultural heritage in CESs, bequest, and education, coincide with the characteristics of cultural heritage. In the previous evaluation system, it was difficult to observe the presentation and evaluation of these values.

Second, the findings highlight the importance of preserving GCH sites, not only for their historical and cultural significance but also for their potential to provide mental and emotional benefits to the community. Urban planners and landscape designers may prioritize the careful conservation of such sites to maintain their unique qualities that contribute to stress reduction and attention restoration. Additionally, in recognition of these sites' potential as stress-reducing and attention-restoring spaces, they could be developed as cultural and recreational hubs within cities. This could involve creating pedestrian-friendly areas, providing seating, and enhancing access to the site, encouraging people to spend more time there and engage with its cultural value.

Third, to help visitors and locals understand a green cultural heritage site's significance and its potential impact on mental well-being, interpretive signage can be installed. This signage could explain the historical context, emphasize the importance of the site for mental restoration, and encourage mindful exploration. Additionally, the successful integration of the stress-reducing and attention-restoring elements with a site's cultural heritage requires collaboration between urban planners and heritage experts. This collaboration can lead to innovative designs that preserve the site's authenticity while enhancing its positive impact on mental well-being.

Last, by recognizing the unique qualities of a GCH site as a stress-reducing and attention-restoring space, urban planning and landscape design can enhance the overall value and importance of such sites in a city. The careful consideration of historical preservation and cultural significance, alongside the well-being of residents and visitors, creates an opportunity to create culturally rich and mentally nourishing urban environments.

Several limitations apply to this study. The current scope of green cultural heritage is still vague, and our study chose only one site and just 64 respondents, which may lead to some limitations, and a new round of evaluation is necessary in the future to increase the findings' validity. Second, there were some limitations in recruiting college students. However, the decision to recruit college students as participants was based on specific considerations for experimental cost. The recruitment of an adult, non-student population requires significant funding in Japan; we did not have sufficient funding, and therefore recruited only a student sample in this exploratory experiment. Additionally, Japan was still in the midst of a pandemic at the time of the survey, so it became very difficult to openly recruit samples, whereas it was relatively easy to organize college students from the university to conduct the survey. Therefore, data from different groups could provide various insights for this topic, and future studies that include participants of different ages, nationalities, occupations, residence times, and cultural backgrounds may be more valuable. Third, additional psychological state scales (e.g., the profile of mood states and anxiety) as well as physiological indicators (e.g., blood pressure, blood oxygen levels, and skin conductance levels) could be applied to measure psychological recovery due to

visiting green cultural heritage sites. Additionally, due to study design and conditioning limitations, we only collected data on subjective perceptions of restorative experiences, which may have some potential bias, although this was a common methodology used in previous studies. Future studies could, for example, consider measuring objective attentional improvement through pre-visit versus post-visit attention test scores. Moreover, a comparison of differences in the restoration experiences between green cultural heritage sites and general green spaces would be valuable. Furthermore, due to time and cost limitations, VR usage could be an effective approach to gathering data in a short time period in future studies.

**Author Contributions:** Conceptualization, J.X.; methodology, J.X. and S.L.; software, J.X.; validation, J.X. and S.L.; formal analysis, J.X.; investigation, J.X., S.L., H.W., J.Z., Q.W., H.L. and J.C.; resources, J.X. and S.L.; data curation, J.X. and S.L.; writing—original draft preparation, J.X.; writing—review and editing, J.X., S.L., H.W., J.Z., Q.W., H.L. and J.C.; visualization, J.X.; supervision, K.F.; project administration, K.F.; funding acquisition, J.X. and K.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Japan Science and Technology Agency (JST SPRING, grant number JPMJSP2109).

**Data Availability Statement:** The original data used in this study are available upon request.

**Acknowledgments:** We would like to thank all experimental participants for their precious time in this study. Additionally, we thank Miss Nakamura, Mr. Qifeng Cai, and Mr. Sihan Zhang for their help in data collection for this study. Moreover, we thank the reviewers and editors for their valuable time in reviewing this manuscript.

**Conflicts of Interest:** The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## Appendix A

**Table A1.** The internal consistency results.

| Items | Cronbach's $\alpha$ | 95% CI Lower Bound | 95% CI Upper Bound |
|---|---|---|---|
| CESs | 0.788 | 0.696 | 0.856 |
| Stress recovery | 0.790 | 0.682 | 0.865 |
| Attention restoration | 0.875 | 0.824 | 0.914 |
| Novelty | 0.701 | 0.545 | 0.809 |
| Escape | 0.853 | 0.783 | 0.904 |
| Fascination | 0.891 | 0.736 | 0.880 |
| Extent | 0.616 | 0.425 | 0.752 |
| Compatibility | 0.840 | 0.767 | 0.893 |

## References

1. Loulanski, T. Revising the concept for cultural heritage: The argument for a functional approach. *Int. J. Cult. Prop.* **2006**, *13*, 207–233. [CrossRef]
2. Sánchez, M.L.; Cabrera, A.T.; Del Pulgar, M.L.G. Guidelines from the heritage field for the integration of landscape and heritage planning: A systematic literature review. *Landsc. Urban Plan.* **2020**, *204*, 103931. [CrossRef]
3. Girard, L.F.; Nocca, F.; Gravagnuolo, A. Matera: City of nature, city of culture, city of regeneration. Towards a landscape-based and culture-based urban circular economy. *Aestimum* **2019**, *74*, 5–42. [CrossRef]
4. Bohnet, I.C.; Molnarova, K.J.; van den Brink, A.; Beilin, R.; Sklenicka, P. How cultural heritage can support sustainable landscape development: The case of Třeboň Basin, Czech Republic. *Landsc. Urban Plan.* **2022**, *226*, 104492. [CrossRef]
5. Fusco Girard, L.; Vecco, M. The "intrinsic value" of cultural heritage as driver for circular human-centered adaptive reuse. *Sustainability* **2021**, *13*, 3231. [CrossRef]
6. Roszczynska-Kurasinska, M.; Domaradzka, A.; Wnuk, A.; Oleksy, T. Intrinsic value and perceived essentialism of culture heritage sites as tools for planning interventions. *Sustainability* **2021**, *13*, 5078. [CrossRef]
7. Seyedashrafi, B.; Ravankhah, M.; Weidner, S.; Schmidt, M. Applying heritage impact assessment to urban development: World heritage property of Masjed-e Jame of Isfahan in Iran. *Sustain. Cities Soc.* **2017**, *31*, 213–224. [CrossRef]

8. Kaya, D.I.; Dane, G.; Pintossi, N.; Koot, C.A. Subjective circularity performance analysis of adaptive heritage reuse practices in the Netherlands. *Sustain. Cities Soc.* **2021**, *70*, 102869. [CrossRef]
9. Alba-Rodríguez, M.D.; Machete, R.; Gomes, M.G.; Falcão, A.P.; Marrero, M. Holistic model for the assessment of restoration projects of heritage housing. Case studies in Lisbon. *Sustain. Cities Soc.* **2021**, *67*, 102742. [CrossRef]
10. Dans, E.P.; González, P.A. The Altamira controversy: Assessing the economic impact of a world heritage site for planning and tourism management. *J. Cult. Herit.* **2018**, *30*, 180–189. [CrossRef]
11. Tan, S.K.; Tan, S.H.; Kok, Y.S.; Choon, S.W. Sense of place and sustainability of intangible cultural heritage–The case of George Town and Melaka. *Tour. Manag.* **2018**, *67*, 376–387. [CrossRef]
12. Ghermandi, A.; Camacho-Valdez, V.; Trejo-Espinosa, H. Social media-based analysis of cultural ecosystem services and heritage tourism in a coastal region of Mexico. *Tour. Manag.* **2020**, *77*, 104002. [CrossRef]
13. Choay, F.; OConnell, L.M. *The Invention of the HISTORIC Monument*, 1st ed.; Cambridge University Press: New York, NY, USA; Cambridge, UK, 2001. (In English)
14. Bučas, J. Problem of green cultural heritage. *J. Archit. Urban.* **2006**, *30*, 19–29. [CrossRef]
15. Deng, L.; Li, X.; Luo, H.; Fu, E.K.; Ma, J.; Sun, L.X.; Huang, Z.; Cai, S.-Z.; Jia, Y. Empirical study of landscape types, landscape elements and landscape components of the urban park promoting physiological and psychological restoration. *Urban For. Urban Green.* **2020**, *48*, 126488. [CrossRef]
16. Luo, S.; Shi, J.; Lu, T.; Furuya, K. Sit down and rest: Use of virtual reality to evaluate preferences and mental restoration in urban park pavilions. *Landsc. Urban Plan.* **2022**, *220*, 104336. [CrossRef]
17. Zhang, K.; Tang, X.; Zhao, Y.; Huang, B.; Huang, L.; Liu, M.; Luo, E.; Li, Y.; Jiang, T.; Wan, J.; et al. Differing perceptions of the youth and the elderly regarding cultural ecosystem services in urban parks: An exploration of the tour experience. *Sci. Total Environ.* **2022**, *821*, 153388. [CrossRef] [PubMed]
18. Kosanic, A.; Petzold, J. A systematic review of cultural ecosystem services and human wellbeing. *Ecosyst. Serv.* **2020**, *45*, 101168. [CrossRef]
19. Benayas, J.M.R.; Newton, A.C.; Diaz, A.; Bullock, J.M. Enhancement of biodiversity and ecosystem services by ecological restoration: A meta-analysis. *Science* **2009**, *325*, 1121–1124. [CrossRef]
20. Cheng, X.; Van Damme, S.; Li, L.; Uyttenhove, P. Evaluation of cultural ecosystem services: A review of methods. *Ecosyst. Serv.* **2019**, *37*, 100925. [CrossRef]
21. Dou, Y.; Zhen, L.; Bakker, M.; Yu, X.; Carsjens, G.J.; Liu, J.; De Groot, R. Investigating the potential impact of ecological restoration strategies on people–landscape interactions through cultural ecosystem services: A case study of Xilin Gol, China. *J. Environ. Manag.* **2022**, *316*, 115185. [CrossRef]
22. Havinga, I.; Bogaart, P.W.; Hein, L.; Tuia, D. Defining and spatially modelling cultural ecosystem services using crowdsourced data. *Ecosyst. Serv.* **2020**, *43*, 101091. [CrossRef]
23. Chan, K.M.; Guerry, A.D.; Balvanera, P.; Klain, S.; Satterfield, T.; Basurto, X.; Bostrom, A.; Chuenpagdee, R.; Gould, R.; Woodside, U.; et al. Where are cultural and social in ecosystem services? A framework for constructive engagement. *BioScience* **2012**, *62*, 744–756. [CrossRef]
24. Kremer, P.; Hamstead, Z.; Haase, D.; McPhearson, T.; Frantzeskaki, N.; Andersson, E.; Kabisch, N.; Larondelle, N.; Rall, E.L.; Elmqvist, T.; et al. Key insights for the future of urban ecosystem services research. *Ecol. Soc.* **2016**, *21*, 29. [CrossRef]
25. Gobster, P.H.; Nassauer, J.I.; Daniel, T.C.; Fry, G. The shared landscape: What does aesthetics have to do with ecology? *Landsc. Ecol.* **2007**, *22*, 959–972. [CrossRef]
26. Zwierzchowska, I.; Hof, A.; Iojă, I.C.; Mueller, C.; Poniży, L.; Breuste, J.; Mizgajski, A. Multi-scale assessment of cultural ecosystem services of parks in Central European cities. *Urban For. Urban Green.* **2018**, *30*, 84–97. [CrossRef]
27. Zhou, L.; Guan, D.; Huang, X.; Yuan, X.; Zhang, M. Evaluation of the cultural ecosystem services of wetland park. *Ecol. Indic.* **2020**, *114*, 106286. [CrossRef]
28. Larson, L.R.; Keith, S.J.; Fernandez, M.; Hallo, J.C.; Shafer, C.S.; Jennings, V. Ecosystem services and urban greenways: What's the public's perspective? *Ecosyst. Serv.* **2016**, *22*, 111–116. [CrossRef]
29. Dickinson, D.C.; Hobbs, R.J. Cultural ecosystem services: Characteristics, challenges and lessons for urban green space research. *Ecosyst. Serv.* **2017**, *25*, 179–194. [CrossRef]
30. Langemeyer, J.; Baró, F.; Roebeling, P.; Gómez-Baggethun, E. Contrasting values of cultural ecosystem services in urban areas: The case of park Montjuïc in Barcelona. *Ecosyst. Serv.* **2015**, *12*, 178–186. [CrossRef]
31. Sánchez, M.L.; Cabrera, A.T.; del Pulgar, M.L.G. The potential role of cultural ecosystem services in heritage research through a set of indicators. *Ecol. Indic.* **2020**, *117*, 106670. [CrossRef]
32. Antrop, M.; Van Eetvelde, V. Landscape perspectives. In *Holistic Nature of Landscape*; Springer: Berlin/Heidelberg, Germany, 2017; Volume 100, pp. 1–23.
33. Schaich, H.; Bieling, C.; Plieninger, T. Linking ecosystem services with cultural landscape research. *Gaia-Ecol. Perspect. Sci. Soc.* **2010**, *19*, 269–277. [CrossRef]
34. White, M.P.; Alcock, I.; Wheeler, B.W.; Depledge, M.H. Would you be happier living in a greener urban area? A fixed-effects analysis of panel data. *Psychol. Sci.* **2013**, *24*, 920–928. [CrossRef] [PubMed]
35. Kim, D.; Jin, J. Does happiness data say urban parks are worth it? *Landsc. Urban Plan.* **2018**, *178*, 1–11. [CrossRef]

36. Yakınlar, N.; Akpınar, A. How perceived sensory dimensions of urban green spaces are associated with adults' perceived restoration, stress, and mental health? *Urban For. Urban Green.* **2022**, *72*, 127572. [CrossRef]
37. Kaplan, S. Meditation, restoration, and the management of mental fatigue. *Environ. Behav.* **2001**, *33*, 480–506. [CrossRef]
38. Ulrich, R.S. View through a window may influence recovery from surgery. *Science* **1984**, *224*, 420–421. [CrossRef] [PubMed]
39. Ulrich, R.S.; Simons, R.F.; Losito, B.D.; Fiorito, E.; Miles, M.A.; Zelson, M. Stress recovery during exposure to natural and urban environments. *J. Environ. Psychol.* **1991**, *11*, 201–230. [CrossRef]
40. Kaplan, S. The restorative benefits of nature: Toward an integrative framework. *J. Environ. Psychol.* **1995**, *15*, 169–182. [CrossRef]
41. Abdulkarim, D.; Nasar, J.L. Are livable elements also restorative? *J. Environ. Psychol.* **2014**, *38*, 29–38. [CrossRef]
42. Grahn, P.; Stigsdotter, U.K. The relation between perceived sensory dimensions of urban green space and stress restoration. *Landsc. Urban Plan.* **2010**, *94*, 264–275. [CrossRef]
43. Hoyle, H.; Hitchmough, J.; Jorgensen, A. All about the 'wow factor'? The relationships between aesthetics, restorative effect and perceived biodiversity in designed urban planting. *Landsc. Urban Plan.* **2017**, *164*, 109–123. [CrossRef]
44. Ratcliffe, E.; Gatersleben, B.; Sowden, P.T. Bird sounds and their contributions to perceived attention restoration and stress recovery. *J. Environ. Psychol.* **2013**, *36*, 221–228. [CrossRef]
45. Wan, C.; Shen, G.Q.; Choi, S. Effects of physical and psychological factors on users' attitudes, use patterns, and perceived benefits toward urban parks. *Urban For. Urban Green.* **2020**, *51*, 126691. [CrossRef]
46. Moran, D. Back to nature? Attention restoration theory and the restorative effects of nature contact in prison. *Health Place* **2019**, *57*, 35–43. [CrossRef] [PubMed]
47. Kaplan, R.; Kaplan, S. *The Experience of Nature: A Psychological Perspective*; Cambridge University Press: Cambridge, UK, 1989.
48. Kaplan, S.; Bardwell, L.V.; Slakter, D.B. The museum as a restorative environment. *Environ. Behav.* **1993**, *25*, 725–742. [CrossRef]
49. Packer, J.; Bond, N. Museums as restorative environments. *Curator Mus. J.* **2010**, *53*, 421–436. [CrossRef]
50. Hidalgo, M.C.; Berto, R.; Galindo, M.P.; Getrevi, A. Identifying attractive and unattractive urban places: Categories, restorativeness and aesthetic attributes. *Medio Ambiente Comport. Hum.* **2006**, *7*, 115–133.
51. Scopelliti, M.; Carrus, G.; Bonaiuto, M. Is it really nature that restores people? A comparison with historical sites with high restorative potential. *Front. Psychol.* **2019**, *9*, 2742. [CrossRef]
52. Memari, S.; Pazhouhanfar, M.; Nourtaghani, A. Relationship between perceived sensory dimensions and stress restoration in care settings. *Urban For. Urban Green.* **2017**, *26*, 104–113. [CrossRef]
53. Peschardt, K.K.; Stigsdotter, U.K. Associations between park characteristics and perceived restorativeness of small public urban green spaces. *Landsc. Urban Plan.* **2013**, *112*, 26–39. [CrossRef]
54. Riechers, M.; Barkmann, J.; Tscharntke, T. Diverging perceptions by social groups on cultural ecosystem services provided by urban green. *Landsc. Urban Plan.* **2018**, *175*, 161–168. [CrossRef]
55. Kopperoinen, L.; Luque, S.; Tenerelli, P.; Zulian, G.; Viinikka, A. 5.5.3. Mapping cultural ecosystem services. In *Mapping Ecosystem Services*; Burkhard, B., Maes, J., Eds.; Pensoft Publishers: Sofia, Bulgaria, 2017; pp. 197–209.
56. Retka, J.; Jepson, P.; Ladle, R.J.; Malhado, A.C.; Vieira, F.A.; Normande, I.C.; Souza, C.N.; Bragagnolo, C.; Correia, R.A. Assessing cultural ecosystem services of a large marine protected area through social media photographs. *Ocean Coast. Manag.* **2019**, *176*, 40–48. [CrossRef]
57. Sherrouse, B.C.; Semmens, D.J.; Clement, J.M. An application of Social Values for Ecosystem Services (SolVES) to three national forests in Colorado and Wyoming. *Ecol. Indic.* **2014**, *36*, 68–79. [CrossRef]
58. Van Riper, C.J.; Foelske, L.; Kuwayama, S.D.; Keller, R.; Johnson, D. Understanding the role of local knowledge in the spatial dynamics of social values expressed by stakeholders. *Appl. Geogr.* **2020**, *123*, 102279. [CrossRef]
59. Xie, J.; Luo, S.; Furuya, K.; Kagawa, T.; Yang, M. A preferred road to mental restoration in the Chinese classical garden. *Sustainability* **2022**, *14*, 4422. [CrossRef]
60. Herzog, T.R.; Maguire, P.; Nebel, M.B. Assessing the restorative components of environments. *J. Environ. Psychol.* **2003**, *23*, 159–170. [CrossRef]
61. Pals, R.; Steg, L.; Siero, F.W.; Van der Zee, K.I. Development of the PRCQ: A measure of perceived restorative characteristics of zoo attractions. *J. Environ. Psychol.* **2009**, *29*, 441–449. [CrossRef]
62. Ivarsson, C.T.; Hagerhall, C.M. The perceived restorativeness of gardens–Assessing the restorativeness of a mixed built and natural scene type. *Urban For. Urban Green.* **2008**, *7*, 107–118. [CrossRef]
63. Felsten, G. Where to take a study break on the college campus: An attention restoration theory perspective. *J. Environ. Psychol.* **2009**, *29*, 160–167. [CrossRef]
64. Luo, S.; Xie, J.; Furuya, K. Assessing the preference and restorative potential of urban park blue space. *Land* **2021**, *10*, 1233. [CrossRef]
65. Arriaza, M.; Cañas-Ortega, J.F.; Cañas-Madueño, J.A.; Ruiz-Aviles, P. Assessing the visual quality of rural landscapes. *Landsc. Urban Plan.* **2004**, *69*, 115–125. [CrossRef]
66. Hermes, J.; Van Berkel, D.; Burkhard, B.; Plieninger, T.; Fagerholm, N.; von Haaren, C.; Albert, C. Assessment and valuation of recreational ecosystem services of landscapes. *Ecosyst. Serv.* **2018**, *31*, 289–295. [CrossRef] [PubMed]
67. Beckmann-Wübbelt, A.; Fricke, A.; Sebesvari, Z.; Yakouchenkova, I.A.; Fröhlich, K.; Saha, S. High public appreciation for the cultural ecosystem services of urban and peri urban forests during the COVID-19 pandemic. *Sustain. Cities Soc.* **2021**, *74*, 103240. [CrossRef]

68. Tabrizian, P.; Baran, P.K.; Smith, W.R.; Meentemeyer, R.K. Exploring perceived restoration potential of urban green enclosure through immersive virtual environments. *J. Environ. Psychol.* **2018**, *55*, 99–109. [CrossRef]
69. Chen, H.; Qiu, L.; Gao, T. Application of the eight perceived sensory dimensions as a tool for urban green space assessment and planning in China. *Urban For. Urban Green.* **2019**, *40*, 224–235. [CrossRef]
70. Stigsdotter, U.K.; Corazon, S.S.; Sidenius, U.; Refshauge, A.D.; Grahn, P. Forest design for mental health promotion—Using perceived sensory dimensions to elicit restorative responses. *Landsc. Urban Plan.* **2017**, *160*, 1–15. [CrossRef]
71. Abkar, M.; Kamal, M.; Maulan, S.; Mariapan, M.; Davoodi, S.R. Relationship between the preference and perceived restorative potential of urban landscapes. *HortTechnology* **2011**, *21*, 514–519. [CrossRef]
72. Wang, R.; Zhao, J.; Meitner, M.J.; Hu, Y.; Xu, X. Characteristics of urban green spaces in relation to aesthetic preference and stress recovery. *Urban For. Urban Green.* **2019**, *41*, 6–13. [CrossRef]
73. Jahani, A.; Saffariha, M. Aesthetic preference and mental restoration prediction in urban parks: An application of environmental modeling approach. *Urban For. Urban Green.* **2020**, *54*, 126775. [CrossRef]
74. Masullo, M.; Ozcevik Bilen, A.; Toma, R.A.; Akin Guler, G.; Maffei, L. The restorativeness of outdoor historical sites in urban areas: Physical and perceptual correlations. *Sustainability* **2021**, *13*, 5603. [CrossRef]
75. Ulrich, R.S. Aesthetic and affective response to natural environment. *Behav. Nat. Environ.* **1983**, *6*, 85–125.
76. Gillihan, S.J.; Kessler, J.; Farah, M.J. Memories affect mood: Evidence from covert experimental assignment to positive, neutral, and negative memory recall. *Acta Psychol.* **2007**, *125*, 144–154. [CrossRef] [PubMed]
77. Ratcliffe, E.; Korpela, K.M. Memory and place attachment as predictors of imagined restorative perceptions of favourite places. *J. Environ. Psychol.* **2016**, *48*, 120–130. [CrossRef]
78. Jiang, B.; Chang, C.Y.; Sullivan, W.C. A dose of nature: Tree cover, stress reduction, and gender differences. *Landsc. Urban Plan.* **2014**, *132*, 26–36. [CrossRef]
79. Hull, R.B., IV; Michael, S.E. Nature-based recreation, mood change, and stress restoration. *Leis. Sci.* **1995**, *17*, 1–14. [CrossRef]
80. Korcz, N.; Janeczko, E.; Bielinis, E.; Urban, D.; Koba, J.; Szabat, P.; Małecki, M. Influence of informal education in the forest stand redevelopment area on the psychological restoration of working adults. *Forests* **2021**, *12*, 993. [CrossRef]
81. Markevych, I.; Schoierer, J.; Hartig, T.; Chudnovsky, A.; Hystad, P.; Dzhambov, A.M.; De Vries, S.; Triguero-Mas, M.; Brauer, M.; Fuertes, E.; et al. Exploring pathways linking greenspace to health: Theoretical and methodological guidance. *Environ. Res.* **2017**, *158*, 301–317. [CrossRef] [PubMed]
82. Nawrath, M.; Elsey, H.; Dallimer, M. Why cultural ecosystem services matter most: Exploring the pathways linking greenspaces and mental health in a low-income country. *Sci. Total Environ.* **2022**, *806*, 150551. [CrossRef] [PubMed]
83. Lindemann-Matthies, P.; Matthies, D. The influence of plant species richness on stress recovery of humans. *Web Ecol.* **2018**, *18*, 121–128. [CrossRef]
84. Nolin, C. The politics of densification and sustainability in urban green heritage spaces. In *Heritage and Sustainable Urban Transformations*; Routledge: London, UK, 2019; pp. 208–218.
85. Stigsdotter, U.K.; Sidenius, U.; Grahn, P. From research to practice: Operationalisation of the eight perceived sensory dimensions into a health-promoting design tool. *Alam Cipta* **2020**, *13*, 57–70.
86. Tilley, C.Y. *A Phenomenology of Landscape: Places, Paths, and Monuments*; Berg: Oxford, UK, 1994; Volume 10.


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Review*

# Scientific Knowledge Map Study of Therapeutic Landscapes and Community Open Spaces: Visual Analysis with CiteSpace

**Yan Han * and Yuehui Liang**

Department of Spatial Culture Design, Kookmin University, Seoul 02707, Republic of Korea; yhleung@126.com
* Correspondence: hanyan0536@foxmail.com

**Abstract:** The pursuit of a healthy and comfortable living environment is a key developmental objective for human society. Therapeutic landscapes play a significant role in improving environmental conditions within these spaces. However, current research suggests that there is still much to be explored in this field, particularly in communal open spaces. Based on the Web of Science literature database and using the CiteSpace visualization tool, this study launched a literature review search on the existing research content on therapeutic landscapes in community spaces by means of publication volume analysis, spatial distribution, keyword analysis, co-citation clustering analysis, keyword timeline, and co-occurring word analysis. Based on the research results, the current status and direction of related research are outlined, and the research hotspots and future trends in this field are analyzed. Current research comprises multiple interdisciplinary branches, such as geography, public space, modern medicine, care, horticultural therapy, urban ecology, and more, with theoretical research, caregiving, spatial territories, and research methodology as the main research vectors. It is clear from this study that the current research on community therapeutic landscapes suffers from a lack of coordination between theoretical and practical development, and the related design practice activities are in a vulnerable stage of development. In terms of the population served, specialized research will be one of the directions of development, as there has been a gradual increase in the number of spatial research on the prevention and complementary treatment of various diseases for subdivided groups. At the same time, the research focus in this field has shifted from the physical health of users to their mental health, leading to a trend of public service development with the objective of social health.

**Keywords:** therapeutic landscapes; community open spaces; mapping knowledge domains; visual analysis; CiteSpace

**Citation:** Han, Y.; Liang, Y. Scientific Knowledge Map Study of Therapeutic Landscapes and Community Open Spaces: Visual Analysis with CiteSpace. *Sustainability* **2023**, *15*, 15066. https://doi.org/10.3390/su152015066

Academic Editors: Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Baojie He and Shi Cheng

Received: 4 September 2023
Revised: 25 September 2023
Accepted: 26 September 2023
Published: 19 October 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The swift evolution of human society has led to an increasing number of cities, expanding urban dimensions, and a growing urban population. As reported by the United Nations, it is predicted that by 2050, roughly 68% of the global population will reside in urban regions [1]. Although prosperous cities offer many conveniences for people's lives, the high population density, buildings, roads, public facilities, etc., constantly encroach on natural spaces in the city, resulting in the serious degradation of the natural environment in high-density urban areas. In addition, unfulfilled innate biophilia [2] instincts in humans may result in chronic physiological or psychological ailments such as hypertension, heart disease, depression, and anxiety [3,4]. In 1995, the World Health Organization (WHO) introduced the idea of healthy cities [5]. Since then, many countries have adopted this concept as a standard for their urban development initiatives. Under the impact of several global public health and safety incidents, "health" has become a key topic of concern in the current society. World Health Day, which focuses on major public health issues affecting the international community, has gradually shifted its theme from focusing on certain diseases or groups to focusing on the health of all people in order to build an equitable and healthy

world, and the theme for 2023 has been designated as "Health for All". On 21 September 2023, a new political declaration was approved at the United Nations Headquarters during a high-level meeting titled, "Universal Health Coverage: Expanding Our Ambition for Health and Well-being in a Post-COVID World". Specifically, governments have pledged to achieve universal health coverage by 2030.

The health benefits of nature are extensive and significant [6]. Although the positive perception people have of nature is evident, the exact confirmation that the natural environment can impact people's health did not occur until 1984, when the environmental psychologist, Roger Ulrich, pioneered the argument that "integrating natural landscapes into therapeutic environments can aid patients in their recovery" [7]. With the introduction of the term "therapeutic landscape" [8], scholars in several countries have initiated a variety of qualitative and quantitative research as well as practical interventions considering the therapeutic role of the landscape. It was demonstrated that landscaped green spaces have a positive correlation with promoting human attention, mood, and physical and mental health. These areas have the potential to build well-being and promote public health and safety [9].

Community open landscape spaces are frequently contacted by urban residents as a natural environment, and they provide an objective advantage for residents' health. They are not only an affordable means of promoting personal development and health benefits, but also a way to build social well-being. Against the backdrop of a high incidence of public health and safety incidents, on World Cities Day 2020, UN Secretary General António Guterres noted that cities have suffered greatly from the current COVID-19 outbreak and that the value of community has been a particular focus of attention during the outbreak. Therefore, concentrating on the design of community open spaces with therapeutic functions plays a pivotal role in taking care of socially disadvantaged groups and achieving equity in green spaces and sustainable lifestyles [10,11].

In this paper, we conduct a systematic review of the research literature on therapeutic landscapes in community spaces from 2000 onwards. Using CiteSpace, we organized and mapped the knowledge domains pertaining to the topic of "health-landscape-community". This approach allowed for an understanding of the therapeutic landscape research trends in community open spaces, an analysis of current research fields, hot spots, and trends in this topic, and the provision of reference information and guidance for future research.

## 2. Materials and Methods

### *2.1. Analytical Methods*

Mapping knowledge domains in scientometrics is a structural representation of the evolution and transformation of scientific knowledge, possessing the dual nature of a "diagram" and a "spectrum" [12,13]. Mapping knowledge domains presents knowledge graphs and genealogies in a visually represented form. CiteSpace is a knowledge visualization software tool that combines the principles of bibliometrics and information visualization [14]. It presents complex relationships such as interactions, evolution, and networks between knowledge units and clusters in an intuitive visual presentation [15]. Through CiteSpace, knowledge mapping allows for a systematic literature review of a particular research field, presenting the research's structure, developmental patterns, and trend detection in graphs and charts that are easy to understand [14,16,17]. Therefore, it can be used to analyze the knowledge structure, evolution patterns, and future directions of the field in an objective and concise manner.

In this paper, CiteSpace 6.2.R1 was used to visualize and analyze the literature data related to community therapeutic landscapes retrieved based on the Web of Science database, and a systematic literature review was conducted on this basis. The current status and trends of research on therapeutic landscapes within community spaces were structured through various analytical methods including spatial distribution, co-occurrence analysis of keywords, co-citation clustering analysis, time zone chart of keywords, and noun term burst detection [18]. This study used CiteSpace knowledge graph visualization to analyze

the literature data in terms of baseline situation, research hotspots, and evolutionary trends, respectively, with the aim of sorting out the current research status and future development trends of therapeutic landscapes related to community environments. In this study, the construction of a knowledge graph (Figure 1) and the analysis and mining of the literature data were carried out in the following steps.

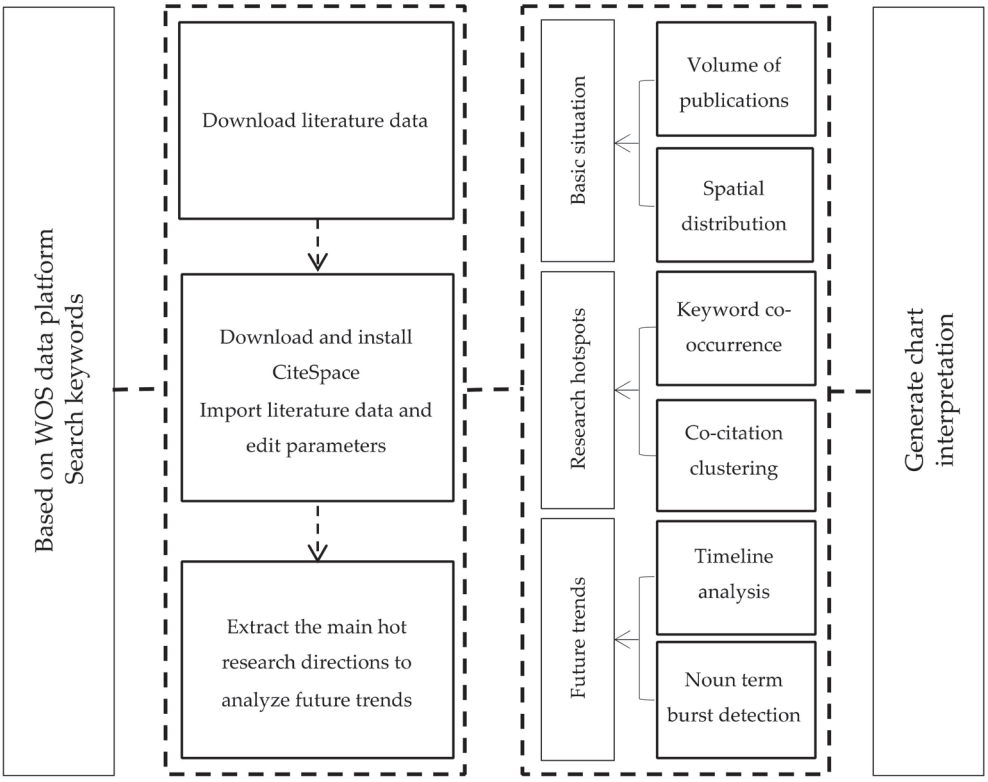



**Figure 1.** Flowchart for building a knowledge graph.

### *2.2. Data Collection*

Web of Science (WOS) is a widely utilized, authoritative literature database that includes four independent databases: SCIE, SSCI, CPCI, and A&HCI. These databases encompass the natural sciences, social sciences, humanities, arts, and other multidisciplinary fields, including journals, conferences, reports, and other forms of the literature. This study was conducted in June 2023 and utilized the WOS Core Aggregate Database as a source of literature data to globally analyze research on therapeutic landscapes within community spaces. To ensure comprehensive and reliable literature data, we made multiple comparisons and adjustments to the search strategy. Finally, we initiated the search on the WOS core ensemble database using the themes "S = (therapeutic landscape OR healing garden OR horticultural therapy) AND (community OR residential) AND language = English". Meanwhile, two types of papers, research papers and literature review papers, were chosen to ensure that the literature data could thoroughly depict the research themes and characteristics. Since the volume of the literature published prior to 2000 ranged from one to three articles annually, the dataset was too limited. Therefore, this paper's search range was limited to 2000–2023, resulting in a total of 1254 pieces of the literature. After filtering out conference proceedings, news items, letters, reviews, and irrelevant fields, 538 valid literature pieces remained as the research data. The data collection steps are shown in Figure 2.

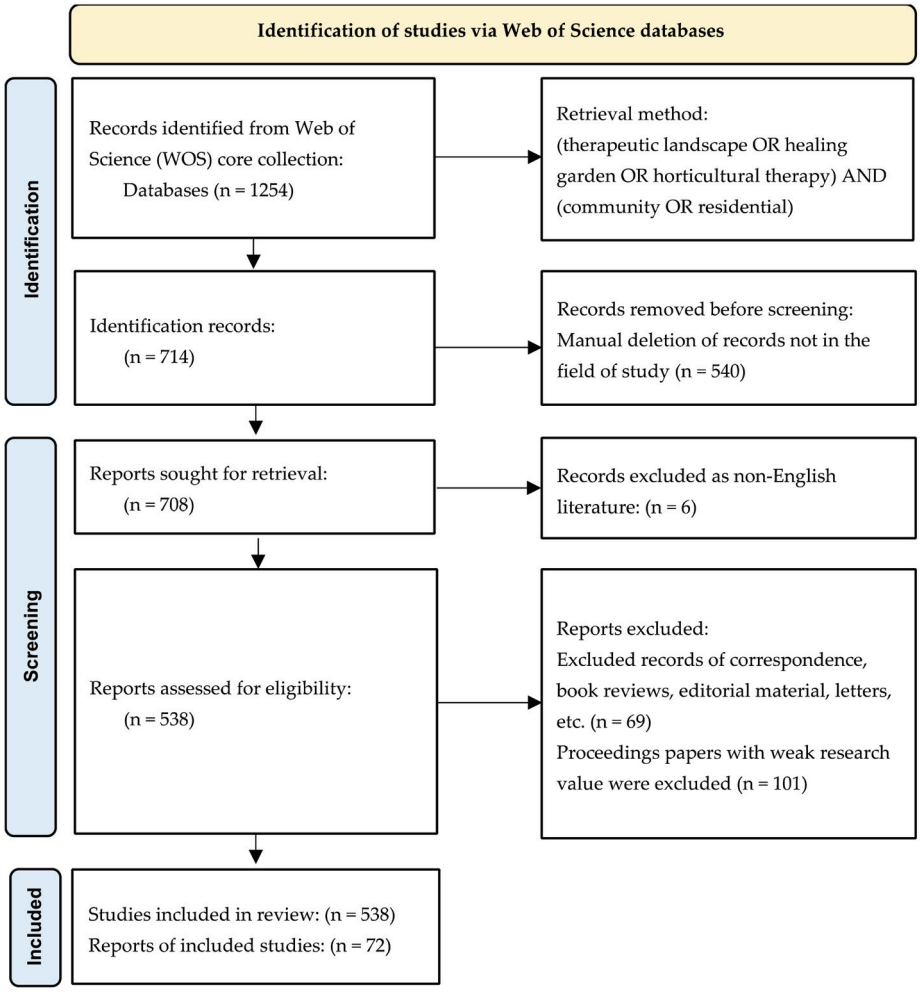



**Figure 2.** The data collection steps.

## 3. Results

### *3.1. An Overview of Basic Research*

#### 3.1.1. Number of Papers Published

The statistical data from this study show a positive correlation between the amount of the research literature about therapeutic landscapes in community spaces and time, with an expected increase in the future (Figure 3). According to the analysis of literature data, the research in this field could be divided into three stages: 2000–2012 is the Fluctuating Exploration Phase, with the growth of research in this phase being fluctuating and slow, the highest annual number of articles being 16, and the lowest annual number of articles being 4, which was extremely unstable; 2013–2016 is the Fluctuating Development Phase, during which the fluctuation still had its ups and downs during the four-year period, but the number of articles increased significantly, and the number of articles was more than 20 during the period of three years; and after 2017, is the Rapid Growth Phase, which had a rapid growth trend of between 30 and 80 annual articles. After 2017, there was a rapid growth phase, in which the annual number of articles between 30 and 80 showed a rapid growth trend, and although there were fluctuations during this period, the number of articles was still considerable. In summary, it is expected that there will be a continued increase in the number of articles in this field in the future.

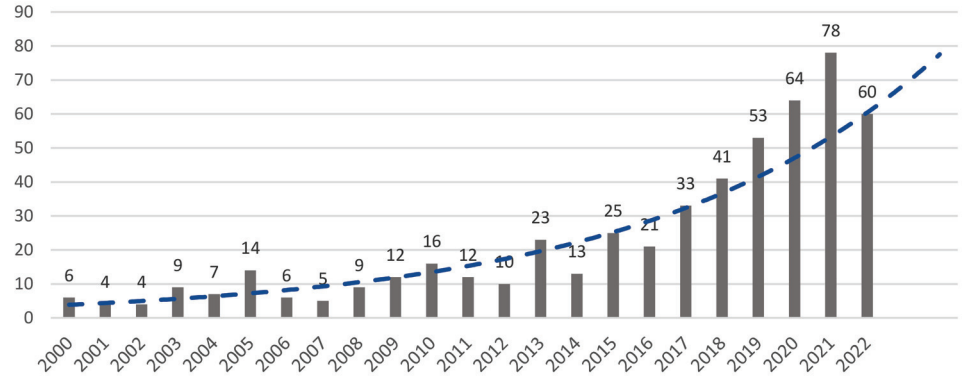



**Figure 3.** Literature Volume and Trend Statistics Related to Rehabilitation Landscapes, 2000–2022 (Statistical Time 4 June 2023). Since the literature data of 2023 are not complete, the statistics and analysis of the number of publications are as of December 2022.

The specific research characteristics of each phase of research related to therapeutic landscapes within community spaces are listed below:

- Fluctuating Exploration Phase (2000–2012): Studies from this period fall into two main categories. The first category is based on the need for human health services, which has driven the introduction of initiatives, concepts related to community services, and programs for community care services and health services. For example, Cattell, Vicky, and others argued that social interaction in public spaces plays an important role in improving people's mental state and maintaining a sense of community and that people gain a sense of well-being through public spaces in their neighborhoods [19]. Wolfe, Mary K., and others, on the other hand, found through their study that urban residential neighborhoods with well-maintained vegetation had a reduced incidence of certain crime types [20]. The second category comprises quantitative research on the effects of natural factors and horticultural activities on human health, again providing data to support the idea that the natural environment and natural activities affect human health. For example, Voeks and colleagues found that being female, older, less illiterate, more educated, and more knowledgeable about medicinal herbs were positively associated with a greater likelihood of having a positive health outcome [21]. Hale-James and others argued that aesthetic relationships are fundamental connections between people and that the stimulation of the senses through horticultural activities, as well as the learning, communication, recognition, and social relationships that result from the horticultural process, contribute to health promotion [22].
- Fluctuating Development Phase (2013–2016): The field of study entered a phase of fluctuating development during this period due to the continued interest in therapeutic landscapes and community open spaces, as well as the emphasis on the health of the population. In this phase, research began to focus on the health needs of "people" in the direction of population segmentation and assistance in alleviating disease; for example, in terms of population, it began to focus on ethnic minorities, refugees, orphans, patients, and people of all ages. In terms of assisting in the alleviation of disease, the main focus was on cancer, Alzheimer's disease, wartime trauma, and other physical and mental illnesses. Extensive quantitative research has also been conducted on the effects on human health of elements of the natural environment, represented by flora and fauna, outdoor facilities, music, and behavioral styles, as well as elements of the artificial environment and human behavior. For example, in the case of plants, Koga, Kazuko, and others found that people experience an unconscious calming response when they touch plants [23]. In terms of behavioral approaches, Doughty argued that social group dynamics, such as walking together, are essential components of many therapeutic landscapes [24]. During this period, research in this area started to have an impact on government policy concerning "well-

being". Dinnie et al. suggested a more in-depth exploration of social relationships and social health in relation to green spaces and their management [25]. Additionally, the integration of traditional gardens with rehabilitated landscapes emerged during that time.

- Rapid Growth Phase (2017–present): This phase of the study on therapeutic landscapes in community open spaces is expanding to multiple disciplines, enabling a more comprehensive interdisciplinary discourse. Research on the characteristics, psychology, behavior, and diseases of diverse populations has become increasingly targeted. Notably, research on the elderly has gained prominence due to the global aging trend [26,27]. Research on the impacts of different natural factors on health and the effects of physical activity in natural settings on health have been investigated more extensively and specifically [28–30]. Quantitative studies on the impact of nature on human health have generated objective experimental data from various multidisciplinary fields [31,32]. These findings can provide more valuable evidence regarding the health benefits of natural environments. On the other hand, while the benefits of nature for human health are well known, healing landscapes are a means of promoting health, not a way of ensuring it. Different forms of therapeutic landscapes can have different effects in different settings; for example, residents of some poor communities do not find weakly attractive, inadequately maintained therapeutic landscapes to be physically and spiritually healing [33].

#### 3.1.2. Spatial Distribution

In terms of the cyberspatial distribution of the established literature data, the countries with a high number of publications in the field of community-based therapeutic landscape research are mainly Europe and the North America, represented by the United States, England, Canada, and Italy, Asia, represented by China and South Korea, and Australia also has a notable presence. In this paper, one year was used as a time slice (2000–2023), and each country was mapped as a node for visualization and analysis (Figure 4). Among them, the United States and England had far more publications than other countries due to their earlier research in the field of therapeutic landscapes. Australia and China, although late in entering the research field, also showed vigorous development.

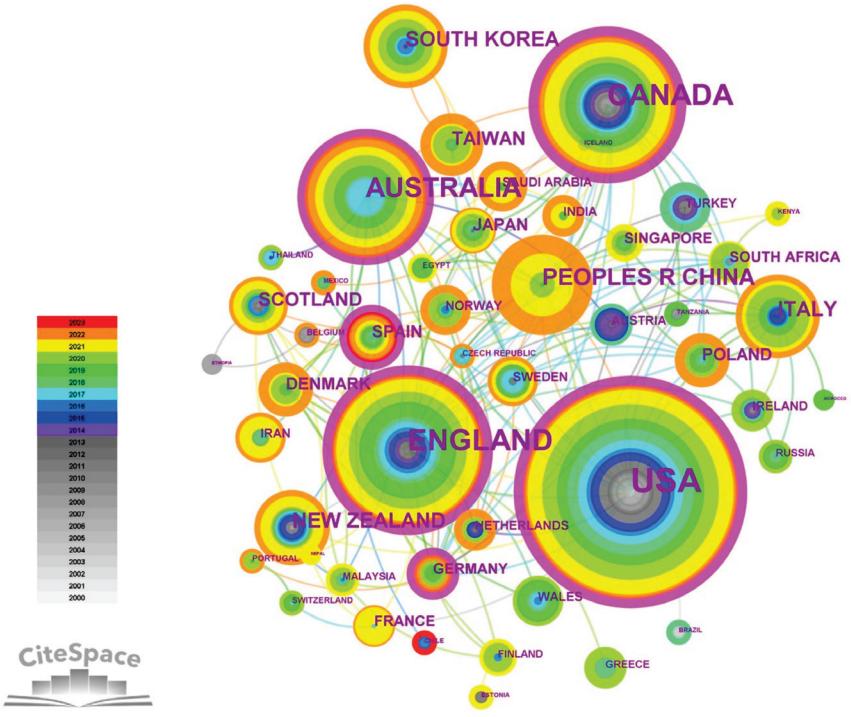



**Figure 4.** Visualization of the country collaboration network from 2000 to 2023.

In CiteSpace, if the betweenness centrality of a node is high, it means that the node plays a pivotal role in that subject area and also plays a vital role in connecting other nodes [34]. For the study of therapeutic landscapes within community spaces, national mediated centrality data (Table 1) were tabulated and categorized into two categories. The first category is represented by England, the United States, Canada, Australia, Germany, and Spain, all of which have a betweenness centrality > 0.1, indicating a high level of importance and influence in this area of study, and they are positioned at the forefront of research in this field. Although some countries have fewer publications, their depth and influence can be significant. For example, even though England started at the same time as the United States in this field, their number of publications is much lower. However, England's betweenness centrality (0.27) is still in first place, indicating that the English literature on community-based therapeutic landscapes is more influential and important than that of other countries. The second category includes Italy, China, Scotland, Japan, and Poland, each having a betweenness centrality value of <0.1 and >0.01. Although these countries have a higher volume of literature in the area of community-based therapeutic landscape research than others, the quality of their output literature is variable, lacking in both breadth and depth compared to the first group of countries. According to the statistics on the number of articles, among the countries with a high number of articles, South Korea has a high number of articles in the field of community therapeutic landscapes, but its betweenness centrality is "0", and although it has a relatively high number of articles, it does not have an impact on other countries.

**Table 1.** Statistics on the number of publications and betweenness centrality of research papers on community therapeutic landscapes.

| Country | Frequency | BC [1] | Time | Country | Frequency | BC [1] | Time |
|---|---|---|---|---|---|---|---|
| United States | 149 | 0.23 | 2000 | New Zealand | 18 | 0.01 | 2003 |
| England | 84 | 0.26 | 2000 | Scotland | 13 | 0.06 | 2002 |
| Canada | 67 | 0.2 | 2002 | Poland | 12 | 0.04 | 2008 |
| Australia | 49 | 0.12 | 2009 | Spain | 10 | 0.1 | 2009 |
| China | 33 | 0.06 | 2009 | Japan | 9 | 0.05 | 2012 |
| South Korea | 20 | 0 | 2010 | Denmark | 9 | 0.03 | 2017 |
| Italy | 20 | 0.07 | 2013 | Germany | 7 | 0.18 | 2013 |

[1] Betweenness centrality (BC): A node metric measuring how likely an arbitrary shortest path in a network is to go through the node, which shows the node-to-node connectivity contribution within a network [35].

This paper concludes by combining studies from countries with a high betweenness centrality and number of publications that have relevant results in this field. The following conclusions were drawn.

1. In Europe and North America, led by the United States and England, research and practical activities related to the integration of natural landscapes into community spaces such as medical resources and social well-being have been relatively prominent and far-reaching, radiating to the "attention to various groups of people, prevention of diseases, and methods of design".
2. Asian countries such as China, Korea, and Japan are more likely to study the connections between plant characteristics and therapeutic landscapes in terms of horticultural therapies, and there has been more research and attention related to the characteristics of elderly users.
3. With the global emphasis on public health and the expectation of a high quality of life, scholars from various nations are increasingly studying therapeutic landscapes in community spaces. These scholars are examining strategies, services, and designs of therapeutic landscapes in community spaces from a variety of perspectives.

Studies in Europe and North America have argued that personalized medicine, based on innovative scientific and social infrastructures and high-quality healthcare facilities, should be equitably distributed in urban communities [35,36] to achieve reciprocity between society and individuals. Among them, reciprocal opportunities are the basis for the

development of healthy communities with heterogeneous groups [37]. Brown, Steven D., and others developed the concept of "vitality" to describe the contribution of the environment to the "feeling of being alive" [38]. Cleary, Anne et al. argue that connecting with nature can help promote well-being and can make a significant contribution to public health [39]. Engineer, Altaf et al. developed an environmental framework for social well-being in seven components: sleep, resilience, environment, exercise, relationships, spirituality, and nutrition [40]. Cravey, A.J., and others argued that socio-spatial knowledge networks (SSKNs) can be used for healthcare prevention strategies and provide design information [41]. Cattell, Vicky et al., proposed a policy approach to the debate about public spaces in relation to well-being and society, arguing that public spaces with therapeutic properties should be widely recognized [19].

In Asian nations, particularly China, Japan, and Korea, horticultural therapy has been researched quantitatively, revealing its capacity to enhance and sustain physical health while encouraging overall mental and emotional well-being via community gardening [26,42,43]. Furthermore, research indicates that individuals may experience an unconscious calming response when in contact with plants [23]. According to Lee, Juyoung, traditional gardens that contain historical and cultural elements also have the ability to reduce negative emotions and function for the well-being of urban residents [44]. Yu, Shiwang et al. showed that social, leisure, and functional activities of older adults in an aging residential community were associated with environmental noise, amenities, and green space [45].

Other nations with a mediator centrality below 0.01 have also demonstrated dynamism in this field of study. For example, in Melbourne, Australia, a settlement environment for young refugees was created. Furthermore, Thai scholars have proposed therapeutic strategies and interventions for the emotional therapeutic landscapes and special cultural needs of female breast cancer patients and the establishment of hospice gardens for the elderly [46,47]. These research studies primarily focus on therapeutic landscapes related to the analysis of the needs of minorities, disadvantaged communities, and other subgroups of user groups. They strive to promote the innovation of user-centered spatial environment creation from multiple perspectives. At the same time, some scholars have paid attention to the possibility of developing therapeutic landscapes in community spaces from the perspective of ethnic identity. To illustrate, researchers have focused on local plants by integrating ethnopharmacology-related content and expanding their functions to edibles, teas, and so on, in order to explore the possible medicinal (health) value, recreational value, and ethnocultural value of landscape plants in the spatial community [48,49]. In addition, some scholars have studied the role of religious emotional sustenance in community therapeutic landscapes from the perspective of religious belief [50,51]. Scholars from different countries have provided relevant research on how design intervenes in the innovation of therapeutic landscapes in community spaces from different perspectives. Among them, Iranian scholars have investigated the role of artificial canals, namely canals, in providing urban health and have proposed a framework for the therapeutic effects of blue-green spaces from a design perspective. To sum up, the participation of more and more researchers has prompted the research on therapeutic landscapes in community spaces to break through traditional research frameworks and methods, trying to diverge from multiple perspectives such as subdividing groups and multidisciplinary integration, and constantly trying to integrate. In order to promote richer and more diversified research among them, there is still a lot of room for innovative research on design interventions in community therapeutic landscapes.

### *3.2. Research Frontiers and Hotspots*

#### 3.2.1. Co-Occurrence of Keywords

Keywords chosen from the title, abstract, and text of the paper are a distillation of the content of the document. This paper starts by analyzing high-frequency keywords and keyword co-occurrences to offer an overview of present trends in development and research hotspots in the field. Among them, high-frequency keywords mean the keywords

with the highest frequency in the analyzed literature data. A high-frequency keyword analysis method is a method used to extract the high and low distributions of keywords or subject words that can express the core content of the literature on the information of literature data and to analyze the current popular research fields and related trends from the visualized data. The simultaneous occurrence of multiple keywords is called keyword co-occurrence, which is a two-by-two count of a set of words in terms of the number of times they appear in the same set of documents, and their proximity is measured by the number of such co-occurrences [12].

In this study, we obtained the co-occurrence mapping of high-frequency keywords related to community therapeutic landscapes by using CiteSpace software, which was run on the WOS database. The results are illustrated in Figure 5. In the graph, each node depicts a keyword, with larger nodes indicating higher frequency. The color of the graph transitions from purple to yellow, with the nodes closer to yellow indicating frequent appearances in the recent literature. In the current international research on therapeutic landscapes in community open spaces, in addition to the keywords, "therapeutic landscapes" and "community" searched for in this paper, high-frequency keywords with a betweenness centrality 1>, such as "geography", "health", and "horticultural therapy", as well as keywords with a betweenness centrality close to 0.1, were also found in this paper. The keywords "mental health" and "place", which have a betweenness centrality close to 0.1, are also hot topics in this research area (Table 2).

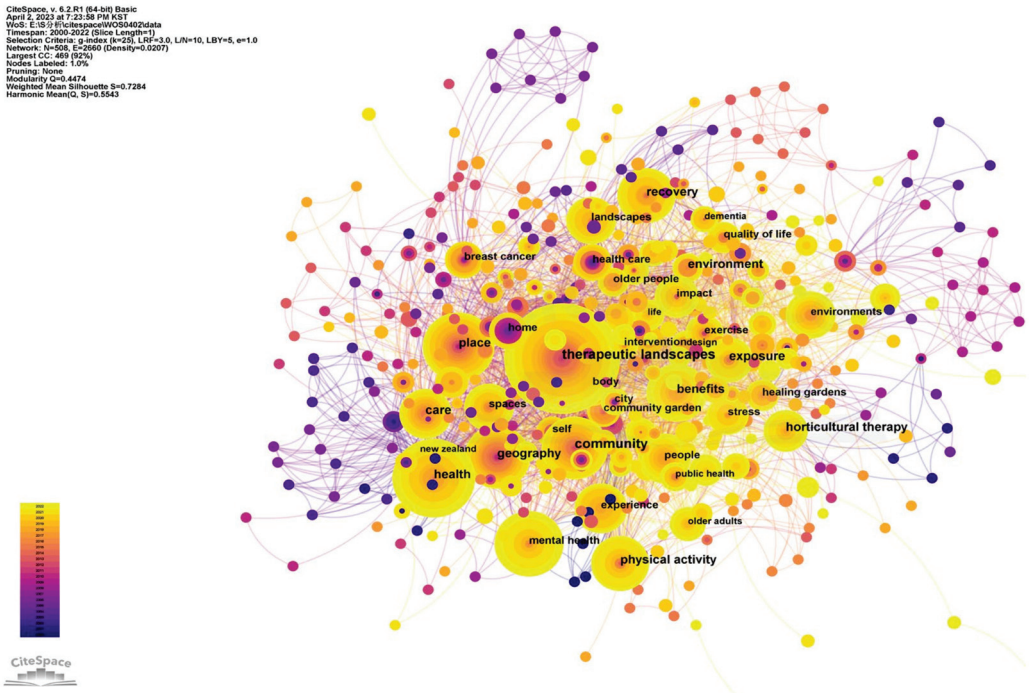



**Figure 5.** Keyword co-occurrence network mapping.

**Table 2.** Community treatment landscape of high-frequency word statistics, 2000–2023.

| High-Frequency Keyword | Frequency | BC | Year |
|---|---|---|---|
| Therapeutic landscapes | 159 | 0.31 | 2001 |
| Community | 55 | 0.18 | 2005 |
| Care | 65 | 0.14 | 2001 |
| Geography | 56 | 0.12 | 2003 |
| Health | 102 | 0.12 | 2004 |
| Horticultural therapy | 38 | 0.11 | 2001 |
| Place | 63 | 0.09 | 2001 |
| Mental health | 53 | 0.09 | 2000 |
| Benefits | 52 | 0.09 | 2002 |
| Breast cancer | 13 | 0.09 | 2006 |

### 3.2.2. Co-Citation Clustering

Citation analysis is the basis of literature co-citation analysis, with scholars citing previous research results in their papers and listing them in the form of references in their studies, thus generating new knowledge, and this constant citation between the scientific literature illustrates the accumulation, continuity, inheritance, as well as disciplinary crossover and penetration of scientific knowledge [12]. Co-cited literature can form multiple reference clusters. Each reference cluster represents a common research topic. The process of mining multiple co-citation relationships through the literature network is known as co-citation analysis of the literature [52]. Analyzing the highly cited literature, which is often the basis for the development of a theme, reveals the progress and direction of research on "community therapeutic landscapes" [13].

The highly cited literature in this research was acquired via CiteSpace utilizing the log likelihood ratio (LLR) algorithm to generate the literature co-citation cluster mapping (Figure 6). The results showed Q = 0.9069 and S = 0.9684, indicating that the clustering network had significant modularity as well as high homogeneity and a significant clustering effect, which could be effectively analyzed. In order to maintain the clarity of the clusters, only the nine clusters with a high number of citations and strong homogeneity were highlighted and sorted, and nine co-cited clusters were finally obtained after screening (Table 3). By reading in detail the frequently cited references in the nine clusters in detail and combining this with the keyword analysis in the previous section, the research hotspots and frontiers of community therapeutic landscapes were deduced.

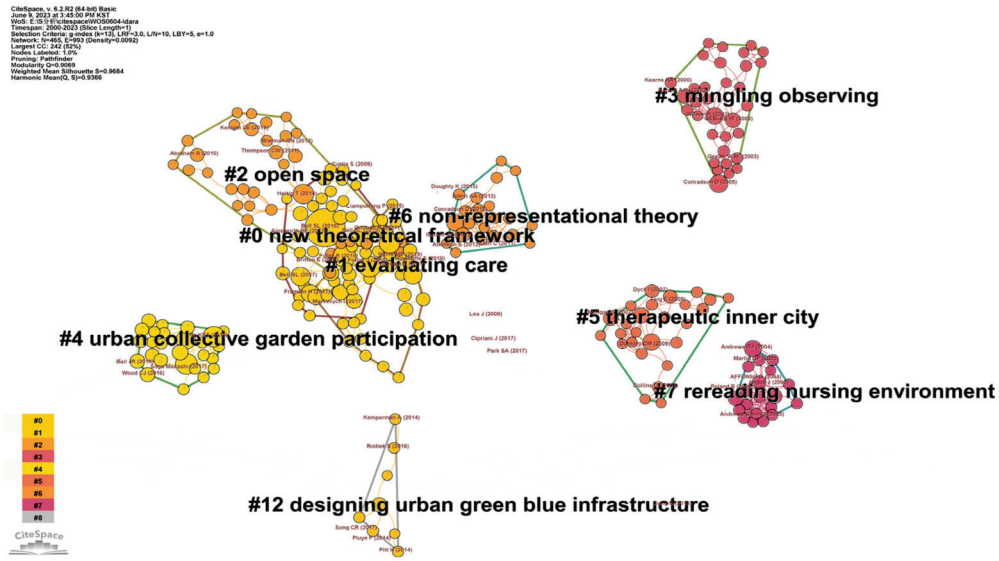



**Figure 6.** Co-citation and cluster analysis of the literature related to therapeutic landscapes and community open spaces.

**Table 3.** Literature co-citation clustering table, 2000–2023.

| Cluster ID | Size | Silhouette | LLR [1] | Average Year |
|---|---|---|---|---|
| #0 | 38 | 0.938 | New theoretical framework | 2016 |
| #1 | 36 | 0.953 | Evaluating care | 2017 |
| #2 | 34 | 0.96 | Open space | 2011 |
| #3 | 33 | 0.994 | Mingling observations | 2002 |
| #4 | 26 | 0.98 | Urban collective garden participation | 2018 |
| #5 | 26 | 0.969 | Therapeutic inner city | 2007 |
| #6 | 21 | 0.976 | Non-representational theory | 2011 |
| #7 | 20 | 1 | Rereading nursing environment | 2003 |
| #12 | 8 | 0.974 | Designing urban green blue infrastructure | 2015 |

[1] Log likelihood ratio (LLR): This is a significant statistical test used for determining whether two or more samples originate from the same probability distribution.

This study summarizes the discovery of four main lines of research and lists the core elements as follows.

1. Theoretical-non-representational theory—A new theoretical framework.

Therapeutic landscape theory, an extension of environmental psychology, cultural (health) geography, medicine, and environmentalism, has gained significant attention and recognition across society since its inception. The concept of therapeutic landscapes acting as cultural landscapes in healthcare proves once again that people are closely linked to their environment, society, and space [8]. As the concept of therapeutic landscapes has been studied intensively, non-representational theories have come to the fore. Non-representational approaches are not strictly speaking theories, but rather ways of comprehending the world and are thus widely employed in the practical realm. Since the focus of non-representational theory has shifted from the study of the intrinsic meaning of things to the subtle and unintentional manifestations and practices of life, it involves making connections to human behavior and the senses [53]. Happiness, viewed as a pursuit for a better life, and its potential impact on health are not only superficial but may also be influenced by environmental factors. Therefore, exploring established concepts and theories within health-related professions and fields could form the basis for future research [54]. The relationship between human behavior, represented by walking, and well-being and health has been theorized as "therapeutic mobility" and can also be explored through activity, connection, and the context that walking improves physical health and mental health [55]. When therapeutic landscape theory and non-representational theory are combined, a new theoretical framework on the field continues to emerge. For example, Sarah L. Bella et al., examined the concept of therapeutic landscapes, mapped key applications of the concept in its core physical, social, spiritual, and symbolic dimensions, and applied the concept to the marginalized in society as a key challenge and suggested that beneficiaries are diverse and differentiated in terms of their health or healing as it develops over time. Diverse understandings of current landscapes, assemblages, and practices across a range of approaches is another key challenge, which Sarah L. et al., argue should be combined with practical physical and psychological measures to facilitate public empathy [9]. Ronan Foley and Thomas Kistemann developed the concept of "blue space" through their research on therapeutic landscapes and the relationship between the environment, health, and well-being, defining blue space as "health-promoting places and spaces where water is at the center of a range of environments with identifiable potential to promote human well-being" [56]. Jessica Finlay et al. extended the concept of therapeutic landscapes by analyzing data from interviews with older adults aged 65–86 and argued that blue spaces should be more prominent in health policy and urban planning for older adults [57].

2. Care—Rereading the nursing environment and evaluating care.

Care can refer to either a limited sense of personal care, where an individual is unable to fulfill their daily physical needs and must depend on others to assist them, or a broader sense of environmental or social care, where nursing activities are carried out within a social sphere [58]. Care in research related to therapeutic landscapes generally refers to care in a broad sense. The extension of healing into the landscape of non-medical environments and the utilization of the landscape's healing power to create "care" in social spaces is one of the most important ways in which therapeutic landscapes can promote social justice. This study found that several scholars have reinterpreted care environments after 2003 and found that care environments of a physical nature should be places with a variety of qualities, care experiences, and places where emotional attachment can be generated; embedding autonomy, quality of life, care, and treatment in this context is a productive and meaningful improvement [59] and therefore incorporating the concept of the therapeutic landscape into aspects of treatment and care can provide direction for the development of healthcare and care environments [60]. The care setting is not limited to the therapeutic environment, but can also be social spaces such as the home and the community, with the overlap of the home and the healthcare space being favored by those being cared for [61].

In the context of the increasing number of care environments, when care environments are shifted to spaces characterized by "local culture", the spatial environment of human settlements in public health discourse is more amenable to health [62], thus promoting social care and social justice. In therapeutic landscapes, caregiving agriculture refers to the use of agricultural practices to promote health, as a way of realizing the integration of social and educational services and as a new way of promoting healing and recovery [63,64]. Thus, horticultural activities, animal care, social communication, and other nature-based interactions are increasingly acknowledged by researchers as health-promoting forms of social care with considerable potential for traumatized psychotherapeutic aspects [65]. In addition to plants, animals play a crucial role in promoting health as an integral aspect of care farming. Therefore, constructing healing spaces should not solely be based on human needs and desires, but also on the position of animals [66]. Sensory experiences are particularly important in therapeutic spaces in terms of healing [67]; for example, Richard Gorman argues that scent positively influences practice and engagement with places and that scent can transcend the audiovisual and be more fully integrated into the therapeutic landscape [68].

3. Place—Geography—Community—Therapeutic inner city—Open space—Designing urban green blue infrastructure—Urban collective garden participation.

In the theory of "sense of place", the subjective nature of human perception of place and the significance of positive subjective feelings in spreading well-being and creating value [69,70] have led to a wide range of research on place since 2001. Health geography is one of the contexts in which the theory of therapeutic landscapes was formed, which argues about landscapes mainly in cultural, theoretical, and medical dimensions [71]. As space has been increasingly studied as a place of meaning, health geography has also approached the study from the perspective of a "place-environment" and recognized the close relationship between therapeutic landscapes and spatial geography [72]. Familiar environments as opposed to unfamiliar environments create place attachment, and people are more inclined to stay in places where they feel safe, comfortable, and have a sense of belonging [73]. The character of therapeutic landscapes changes in response to different environmental changes due to the variability in natural environments, economic circumstances, cultural beliefs, and ethnic identities. Geographies of well-being, for example, are inspired by indigenous cultures and geographies of health, emphasizing the cultural specificity of indigenous landscapes and the need for therapeutic landscapes to change based on changes in the environment of the location [74]. As the study of therapeutic landscapes in terms of place and geography progresses, communities are characterized by a sense of place as well as unique cultural and health geographies, making them spatial environments that can be further developed. In addition, communities are important in terms of a sense of belonging, social interaction, liberation from the margins of society, and solidarity against oppression. It has been found that therapeutic landscapes formed by people as subjects engaging and communicating with the natural environment through interactions in taskscapes [75] and retreats [76] can greatly contribute to the development of community-based urban environmental justice [77]. Currently, because of the uneven development of research on nature for health, the therapeutic role of the natural environment should be actively and critically embraced [78,79], the formation of healing cities should be reached from the perspective of therapeutic landscapes in communities, and healing city research should be extended to a wide range of open spaces. By triggering interactions with cultural, geographic, and economic groups in open spaces, landscapes that promote high-quality interactions between people and nature [80] are important for achieving social integration, social participation, social support, and social security, and thus, social well-being [81]. As people age, their mobility tends to decline, along with a reduction in both their space and the range of activities they are able to undertake. At present, the availability of trees and grass, along with perceptions of greenery, are the primary factors impacting social connections among neighbors in community spaces [82]. In addition, there is a greater preference for natural, aesthetically pleasing, and diverse landscaping, as well as spatial

environments featuring good infrastructure and easy accessibility [83,84]. In addition, horticultural therapy in urban collective garden participation is also prominent in this regard. Therefore, the integration of horticultural therapy into public gardening can not only improve physical, mental, and social health [85]. In the long run through the feasibility of horticultural therapy interventions [86], it can also alleviate and prevent various health problems currently faced by society [87,88], thereby improving social well-being [26].

4. Mingling observations.

In the study of community open space, scholars usually use mixed methods represented by observing the site, semi-structured interviews, qualitative research, and quantitative experiments to study open space and reach a consensus on the unique healing characteristics that a community open space possesses, such as comfort, inclusiveness, ethnicity, and culture [19]. For example, Kathleen Wilson researched the relationship between place and health in specific cultural contexts through interviews, arguing that culture is an important part of open spaces in everyday life [89]. David Conradson, on the other hand, argued that the therapeutic landscape is best approached as a relational outcome, as a series of exchange scenarios that pass between the individual and his or her wider social environment [90]. In addition, Christine Milligan and colleagues conducted a study on the health impacts of public gardening activities, using observation, testing, and semi-structured interviews. Their findings suggested that gardening activities can lead to a sense of accomplishment, satisfaction, and aesthetic pleasure and that public gardening activities promote inclusivity by creating shared spaces [61]. Tanja Schmidt and her colleagues conducted a quantitative study of community open spaces using observation and interviews. Their findings concluded that social interaction is a pivotal factor in the utilization of community open spaces amongst older individuals [91].

### *3.3. Future Evolutionary Trends*

#### 3.3.1. Keyword Timeline

A timeline map is a visualization map constructed on the basis of keyword co-occurrence according to the year of keyword appearance, which can intuitively reflect the hot keywords of therapeutic landscapes in community space in each year of the research process, according to which we can further understand the stage of development and developmental trends of the research, and on the basis of which we can make a certain degree of predictions on the future direction of the research [16].

As shown in Figure 7, before 2000 was the beginning stage of therapeutic landscape research in community spaces. In 2000–2015, quality of life became a hot topic in the field of therapeutic landscapes and combined with healing gardens, horticultural therapy, green space, and healing environments under the joint research, the research in the field of therapeutic landscapes in community spaces was promoted. There was limited research on therapeutic landscapes in community spaces from 2015 to 2019, with a majority of studies focused on traditional topics. A few studies explored nature-based interventions, civic ecology, modern medicine, space and place, with horticultural therapies emerging as a popular research topic in 2018–2019. The frequent outbreaks of public health and wellness events from 2019 to 2023 have brought community values and wellness to the forefront of people's minds, prompting research on healing gardens, horticultural therapies, and more to remain able to maintain a considerable amount of fervor. Researchers' attention to nature-based interventions such as community gardens, green spaces, and quality of life is gradually increasing, and the soundscape represented by "music" has become a new research hotspot at this stage. In addition, the relationship between therapeutic landscapes and quality of life has become the most important research direction for researchers through literature data.

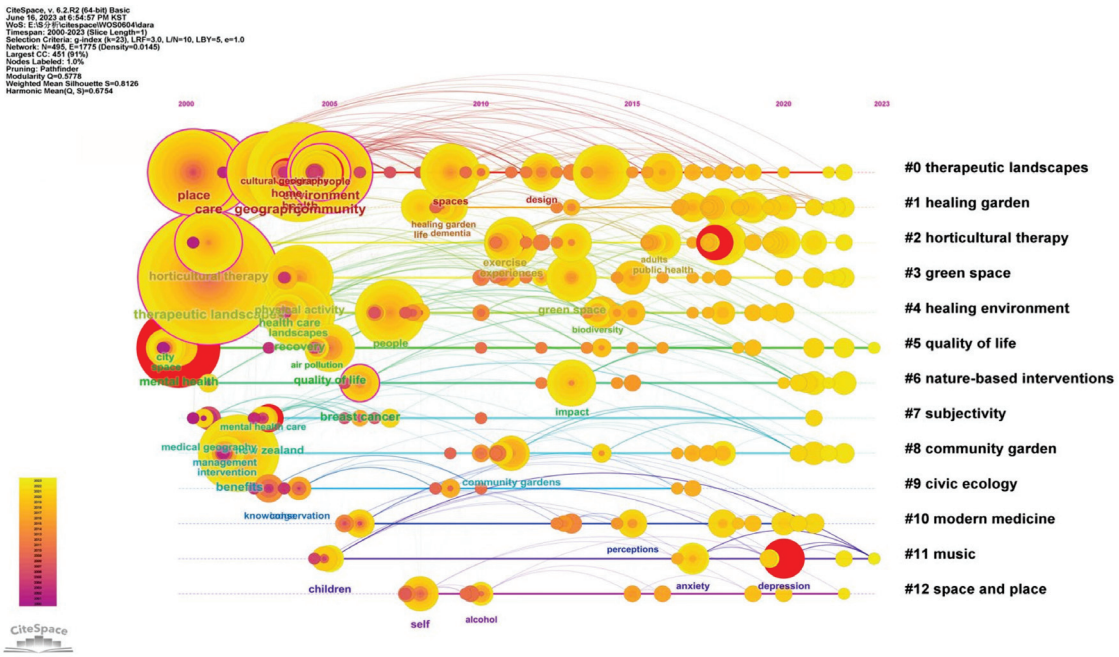



**Figure 7.** Spatial timeline map analysis of community therapeutic landscapes.

### 3.3.2. Noun Term Burst Detection

Burst strength represents the prominence rate of keywords, which can reflect the more influential research areas in a period of time, representing the research hotspots and scientific development research trends in a specific time. A total of 84 burst noun terms were obtained through CiteSpace keyword bursting and burst time visualization. Table 4 shows the 20 most frequent groups of terms.

**Table 4.** Top 20 high-frequency terms and their burst time.

| Keyword [1] | Year [2] | Strength [3] | Begin [4] | End [5] | 2000–2023 |
|---|---|---|---|---|---|
| Medical geography | 2001 | 2.45 | 2001 | 2006 | |
| Home | 2004 | 4.97 | 2004 | 2010 | |
| Self | 2008 | 1.92 | 2008 | 2010 | |
| Geography | 2003 | 2.62 | 2012 | 2016 | |
| Quality of life | 2005 | 2.79 | 2014 | 2016 | |
| Older people | 2005 | 4.13 | 2016 | 2018 | |
| Environment | 2005 | 3.97 | 2016 | 2017 | |
| Community gardens | 2011 | 2.2 | 2017 | 2018 | |
| Experiences | 2011 | 3.37 | 2018 | 2019 | |
| Landscapes | 2004 | 2.97 | 2019 | 2020 | |
| Framework | 2019 | 2.41 | 2019 | 2020 | |
| Therapy | 2019 | 1.93 | 2019 | 2020 | |
| Depression | 2020 | 3.61 | 2020 | 2023 | |
| Stress | 2008 | 2.31 | 2020 | 2021 | |
| Walking | 2020 | 2.31 | 2020 | 2023 | |
| Ecosystem services | 2020 | 2.03 | 2020 | 2021 | |
| Impact | 2013 | 1.83 | 2020 | 2023 | |
| Mental health | 2000 | 3.37 | 2021 | 2023 | |
| Mortality | 2021 | 2.07 | 2021 | 2023 | |
| Green space | 2013 | 2.05 | 2021 | 2023 | |

[1] Keyword: represents explosive noun words; [2] Year: indicates the year when the keyword begins to appear; [3] Strength: indicates the strength of the outbreak; [4] Begin: represents the beginning year of the outbreak of the noun term; [5] End: indicates the end year of the outbreak; The blue lines show when the keywords started and the red lines show the durations of the bursts.

Research topics related to the impact of landscape space on health have been popular among scholars in various countries during the period 2000–2023. Since this field of research was first extended from the fields of environmental psychology, health geography, and medicine, with a focus on the human environment, "medical geography, home, and self" became the first bursts of keywords to become prominent in the years 2001–2010. At this stage, research in the field of medical geography was not only focused on medical environments, but also on residential environments in terms of burst strength and duration, and on the basis of this, on the needs of human beings for their own environments. Since 2012, geography has been at the center of therapeutic landscape research theory for the past five years. During the period when geography was a popular subject, research related to the living environment, the living experience, and the living population iterated with each other on a yearly basis and became a popular research topic, which promoted the development of the research field from multiple perspectives, of which the topic of "elderly" had the most burst strength. Until 2019, the research on the healing nature of landscapes has gradually formed a variety of frameworks, while the healing and facilitating effects of landscapes on psychological aspects has received the attention of more scholars and gradually become one of the main directions in the field of therapeutic landscape research, demonstrating the continuous development and evolution of this research field from the macro to micro levels, from theory to practice, and from the physical environment to the spiritual environment. Mental health research has always existed throughout the entire therapeutic landscape research field, since 2000, and therapeutic landscape-related mental health research was always of high concern but did not form bursts until 2020, in the world of public health and safety outbreaks, leading people to produce "stress, depression" and other emotions, which advanced to 2021 with "mental health" as a keyword for the formation of the strong bursts, along with community therapeutic landscape research into the "focus on mental health-oriented urban green space landscape ecological service". In addition, attention to the mortality rate in the context of population aging is also rising and has become a new research hotspot.

## 4. Discussion and Prospects

Community open space as one of the carriers of urban landscape space, how to use community open space to maximize the possibility of landscape space unique healing, to achieve the role of promoting physical, mental, and social health, and thus improve social well-being, is the main goal of the current community therapeutic landscape-related research, and the same is also for the development of today's social life, the political orientation and the development of the system of attention to content.

Throughout this literature research collation, since 2000, therapeutic landscapes in community open spaces research gradually formed a scale. This paper is based on the community therapeutic landscape of the research objectives, through CiteSpace scientific knowledge mapping visualization and analysis which found that, at present, from the perspective of the amount of articles issued, the current research in this field has entered a stage of rapid growth, and the research on medicine, geography, design, behavior, sociology, and so on between the multidisciplinary discussions is more rich as the most significant feature of this stage. From the results of the visualization study of the spatial distribution of the relevant literature data, Europe and the United States focus on qualitative and quantitative research, while Asian countries are more focused on practical research, and due to the earlier involvement of Europe and the United States in this research field, the impact of the relevant research in Europe and the United States and the quality of the literature is higher than that of the countries. The hotspots of research in this field developed to the present are mainly focused on geography, horticultural therapy, mental health, and so on. It can be seen that the focus of research has shifted from the pure pursuit of quality of life and passive perception of the healing effect of the landscape, to the active experience and perception aspects in the landscape space, but also from the initial pursuit of physiological health research, to focus on the user's multi-level health needs in terms of mental health

and spiritual health research. An examination of research techniques regarding therapeutic landscapes in community spaces indicates that traditional mixed research methods, including behavioral observation, social science statistics, and quantitative testing and analysis, are still more frequently employed. The research encompasses three primary research directions focused on theory, care, and place. Specifically, new theories and design frameworks extended from theories related to therapeutic landscapes and non-representational theories; extending from the narrow definition of caring care to the environment, deriving care activities in non-medical environments, and building on this foundation, such as landscape character extraction and landscape evaluation; as well as place-based research on open space, therapeutic infrastructure, and public engagement.

At the same time, this paper examines the trends in the research field of community therapeutic landscapes through the analysis and organization of CiteSpace's scientific knowledge map. The examination will focus on three areas: application practice, service targets, and service direction. In the application practice, the current community therapeutic landscape research still exists in regional development of the situation and is not coordinated, although the existing research presents a large number of quantitative and qualitative research content on the design of the practice but is still in a weak position, which provides more possibilities for relevant researchers to intervene in the practice of the activities, to promote the community therapeutic landscape continues to develop and innovate. However, studies focusing on subdivided groups tend to primarily focus on minority groups, while research on community-based therapeutic environments for overall health remains prevalent. Therefore, subdivision should be considered based on the prevailing research. In terms of service targets, research on special groups represented by the elderly, as well as spatial research on the prevention and complementary treatment of various types of diseases, has shown an increasing trend, which provides a theoretical basis for research based on the needs of a particular subgroup, and at the same time breaks the concept of the traditional community therapeutic landscape and promotes its development from the perspective of the user's needs more often. In the service direction, with the gradual improvement in medical conditions, the current spiritual needs of people are on the rise, reflected in the community open space requirements in addition to facilities to meet the needs of physiological health, should be more spiritual aspects of service to achieve the purpose of promoting mental health. Similarly, horticultural therapy, as a current means of natural active healing, should be optimized in terms of service and jointly promote the development of social public services. The service aspect can be integrated with service design and other disciplines to form a therapeutic landscape service design system within the community space. In summary, research and practice related to therapeutic landscapes in community open spaces is still at an early stage and has significant potential for growth. Currently, a lack of balance and insufficient volume of publications, spatial distribution, and theoretical research, practical inquiry, and research methodology exists. Consequently, there is a need to integrate various spaces, disciplines, and approaches to explore the development of therapeutic landscapes within communities.

**Author Contributions:** Conceptualization, Y.H.; methodology, Y.H.; software, Y.H.; validation, Y.H. and Y.L.; formal analysis, Y.L.; investigation, Y.H.; resources, Y.H.; data curation, Y.H.; writing—original draft preparation, Y.H.; writing—review and editing, Y.H. and Y.L.; visualization, Y.H.; supervision, Y.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The articles were obtained from Web of Science (https://www.webofscience.com/, accessed on 4 June 2023).

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. UN News. World Cities Day: Value Communities, Today and for the Future. 29 October 2020. Available online: https://news.un.org/en/story/2020/10/1076402 (accessed on 2 July 2023).
2. Wilson, E.O. *Biophilia*; Harvard University Press: Cambridge, MA, USA, 1984.
3. Bin, J.; Tian, Z.; William, C.S.; Xiao, W. Healthy Cities: Mechanisms and Resarch Questions Regarding the Impacts of Urban Green Landscapes on Public Health and Well-Being. *Landsc. Archit. Front.* **2015**, *3*, 24–35.
4. Thompson, C.W. Linking landscape and health: The recurring theme. *Landsc. Urban Plan.* **2011**, *99*, 187–195. [CrossRef]
5. World Health Organization. *WHO Healthy Cities: A Programme Framework: A Review of the Operation and Future Development of the WHO Healthy Cities Programme*; WHO: Geneva, Switzerland, 1995; p. 20.
6. Shuhua, L.; Yanan, Y.; Chang, L.; Ning, K. The Effect and Mechanism of GreenSpace on Human Physical and Mental Health:A Proposal of Green Medicine. *Chin. Landsc. Archit.* **2019**, *35*, 5–11. [CrossRef]
7. Ulrich, R.S. View through a window may influence recovery from surgery. *Science* **1984**, *224*, 420–421. [CrossRef] [PubMed]
8. Gesler, W.M. Therapeutic landscapes: Medical issues in light of the new cultural geography. *Soc. Sci. Med.* **1992**, *34*, 735–746. [CrossRef] [PubMed]
9. Bell, S.L.; Foley, R.; Houghton, F.; Maddrell, A.; Williams, A.M. From therapeutic landscapes to healthy spaces, places and practices: A scoping review. *Soc. Sci. Med.* **2018**, *196*, 123–130. [CrossRef] [PubMed]
10. Skalicky, V.; Čerpes, I. Comprehensive assessment methodology for liveable residential environment. *Cities* **2019**, *94*, 44–54. [CrossRef]
11. Marques, B.; McIntosh, J.; Kershaw, C. Therapeutic environments as a catalyst for health, well-being and social equity. *Landsc. Res.* **2021**, *46*, 766–781. [CrossRef]
12. Jie, L.; Chaomei, C. *CiteSpace: Text Mining and Visualization in Scientific Literature*, 2nd ed.; Capital University of Economics and Business Press: Beijing, China, 2017.
13. Ying, J.; Zhang, X.; Zhang, Y.; Bilan, S. Green infrastructure: Systematic literature review. *Econ. Res. Ekon. Istraživanja* **2022**, *35*, 343–366. [CrossRef]
14. Chen, C. Cite Space II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *J. Am. Soc. Inf. Sci. Technol.* **2006**, *57*, 359–377. [CrossRef]
15. Ellegaard, O.; Wallin, J.A. The bibliometric analysis of scholarly production: How great is the impact? *Scientometrics* **2015**, *105*, 1809–1831. [CrossRef] [PubMed]
16. Chen, Y.; Chen, C.M.; Liu, Z.Y.; Hu, Z.G.; Wang, X.W. The methodology function of Cite Space mapping knowledge domains. *Stud. Sci. Sci.* **2015**, *33*, 242–253. [CrossRef]
17. Chen, C. Searching for intellectual turning points: Progressive knowledge domain visualization. *Proc. Natl. Acad. Sci. USA* **2004**, *101* (Suppl. S1), 5303–5310. [CrossRef] [PubMed]
18. Wu, Y.; Wang, H.; Wang, Z.; Zhang, B.; Meyer, B.C. Knowledge mapping analysis of rural landscape using CiteSpace. *Sustainability* **2019**, *12*, 66. [CrossRef]
19. Cattell, V.; Dines, N.; Gesler, W.; Curtis, S. Mingling, observing, and lingering: Everyday public spaces and their implications for well-being and social relations. *Health Place* **2008**, *14*, 544–561. [CrossRef] [PubMed]
20. Wolfe, M.K.; Mennis, J. Does vegetation encourage or suppress urban crime? Evidence from Philadelphia, PA. *Landsc. Urban Plan.* **2012**, *108*, 112–122. [CrossRef]
21. Voeks, R.A.; Leony, A. Forgetting the forest: Assessing medicinal plant erosion in eastern Brazil. *Econ. Bot.* **2004**, *58*, S294–S306. [CrossRef]
22. Hale, J.; Knapp, C.; Bardwell, L.; Buchenau, M.; Marshall, J.; Sancar, F.; Litt, J.S. Connecting food environments and health through the relational nature of aesthetics: Gaining insight through the community gardening experience. *Soc. Sci. Med.* **2011**, *72*, 1853–1863. [CrossRef]
23. Koga, K.; Iwasaki, Y. Psychological and physiological effect in humans of touching plant foliage-using the semantic differential method and cerebral activity as indicators. *J. Physiol. Anthropol.* **2013**, *32*, 7. [CrossRef]
24. Doughty, K. Walking together: The embodied and mobile production of a therapeutic landscape. *Health Place* **2013**, *24*, 140–146. [CrossRef]
25. Bell, S.L.; Phoenix, C.; Lovell, R.; Wheeler, B.W. Seeking everyday wellbeing: The coast as a therapeutic landscape. *Soc. Sci. Med.* **2015**, *142*, 56–67. [CrossRef]
26. Ng, K.; Sia, A.; Ng, M.; Tan, C.; Chan, H.; Tan, C.; Rawtaer, I.; Feng, L.; Mahendran, R.; Larbi, A.; et al. Effects of Horticultural Therapy on Asian Older Adults: A Randomized Controlled Trial. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1705. [CrossRef]
27. Zhu, B.W.; Zhang, J.R.; Tzeng, G.H.; Huang, S.L.; Xiong, L. Public Open Space Development for Elderly People by Using the DANP-V Model to Establish Continuous Improvement Strategies towards a Sustainable and Healthy Aging Society. *Sustainability* **2017**, *9*, 420. [CrossRef]
28. Dorn, S.; Bradley, L.; Hamrick, D.; Weisenhorn, J.; Bennett, P.; Callabro, J.; Behe, B.; Bauske, E.; Bumgarner, N. The National Initiative for Consumer Horticulture: Focusing on the critical role of communication and collaboration to further research, extension, and industry goals. *HortTechnology* **2018**, *28*, 414–421. [CrossRef]
29. Schmidt, T.; Kerr, J.; Schipperijn, J. Associations between Neighborhood Open Space Features and Walking and Social Interaction in Older Adults—A Mixed Methods Study. *Geriatrics* **2019**, *4*, 41. [CrossRef] [PubMed]

30. Edmonds, S.E. Geographies of (Cross)fitness: An ethnographic case study of a CrossFit Box. *Qual. Res. Sport Exerc. Health* **2019**, *71*, 280–287. [CrossRef]
31. Elsadek, M.; Sun, M.; Sugiyama, R.; Fujii, E. Cross-cultural comparison of physiological and psychological responses to different garden styles. *Urban For. Urban Green.* **2019**, *38*, 74–83. [CrossRef]
32. Lassell, R.; Wood, W.; Schmid, A.A.; Cross, J.E. A comparison of quality of life indicators during two complementary interventions: Adaptive gardening and adaptive riding for people with dementia. *Complement. Ther. Med.* **2021**, *57*, 102658. [CrossRef] [PubMed]
33. Triguero-Mas, M.; Anguelovski, I.; García-Lamarca, M.; Argüelles, L.; Perez-del-Pulgar, C.; Shokry, G.; Connolly, J.J.; Cole, H.V. Natural outdoor environments' health effects in gentrifying neighborhoods: Disruptive green landscapes for underprivileged neighborhood residents. *Soc. Sci. Med.* **2021**, *279*, 113964. [CrossRef] [PubMed]
34. Freeman, L.C. Centrality in social networks. Conceptual clarification. *Soc. Netw.* **1979**, *1*, 215–239. [CrossRef]
35. Lesko, L.J. Personalized medicine: Elusive dream or imminent reality? *Clin. Pharmacol. Ther.* **2007**, *81*, 807–816. [CrossRef] [PubMed]
36. Hawthorne, T.L.; Kwan, M.P. Using GIS and perceived distance to understand the unequal geographies of healthcare in lower-income urban neighbourhoods. *Geogr. J.* **2012**, *178*, 18–30. [CrossRef] [PubMed]
37. Letcher, A.S.; Perlow, K.M. Community-based participatory research shows how a community initiative creates networks to improve well-being. *Am. J. Prev. Med.* **2009**, *37*, S292–S299. [CrossRef] [PubMed]
38. Brown, S.D.; Reavey, P. Vital spaces and mental health. *Med. Humanit.* **2019**, *45*, 131–140. [CrossRef] [PubMed]
39. Cleary, A.; Fielding, K.S.; Bell, S.L.; Murray, Z.; Roiko, A. Exploring potential mechanisms involved in the relationship between eudaimonic wellbeing and nature connection. *Landsc. Urban Plan.* **2017**, *158*, 119–128. [CrossRef]
40. Engineer, A.; Gualano, R.J.; Crocker, R.L.; Smith, J.L.; Maizes, V.; Weil, A.; Sternberg, E.M. An integrative health framework for wellbeing in the built environment. *Build. Environ.* **2021**, *205*, 108253. [CrossRef]
41. Cravey, A.J.; Washburn, S.A.; Gesler, W.M.; Arcury, T.A.; Skelly, A.H. Developing socio-spatial knowledge networks: A qualitative methodology for chronic disease prevention. *Soc. Sci. Med.* **2001**, *52*, 1763–1775. [CrossRef] [PubMed]
42. Lu, S.; Wu, F.; Wang, Z.; Cui, Y.; Chen, C.; Wei, Y. Evaluation system and application of plants in healing landscape for the elderly. *Urban For. Urban Green.* **2021**, *58*, 126969. [CrossRef]
43. Park, S.A.; Lee, K.S.; Son, K.C. Determining exercise intensities of gardening tasks as a physical activity using metabolic equivalents in older adults. *HortScience* **2011**, *46*, 1706–1710. [CrossRef]
44. Lee, J. Experimental study on the health benefits of garden landscape. *Int. J. Environ. Res. Public Health* **2017**, *14*, 829. [CrossRef]
45. Yu, S.; Guo, N.; Zheng, C.; Song, Y.; Hao, J. Investigating the association between outdoor environment and outdoor activities for seniors living in old residential communities. *Int. J. Environ. Res. Public Health* **2021**, *18*, 7500. [CrossRef]
46. Sampson, R.; Gifford, S.M. Place-making, settlement and well-being: The therapeutic landscapes of recently arrived youth with refugee backgrounds. *Health Place* **2010**, *16*, 116–131. [CrossRef] [PubMed]
47. Liamputtong, P.; Suwankhong, D. Therapeutic landscapes and living with breast cancer: The lived experiences of Thai women. *Soc. Sci. Med.* **2015**, *128*, 263–271. [CrossRef] [PubMed]
48. Sõukand, R.; Kalle, R. Where does the border lie: Locally grown plants used for making tea for recreation and/or healing, 1970s–1990s Estonia. *J. Ethnopharmacol.* **2013**, *150*, 162–174. [CrossRef] [PubMed]
49. Molares, S.; Ladio, A. Medicinal plants in the cultural landscape of a Mapuche-Tehuelche community in arid Argentine Patagonia: An eco-sensorial approach. *J. Ethnobiol. Ethnomed.* **2014**, *10*, 61. [CrossRef] [PubMed]
50. Williams, A. Spiritual landscapes of Pentecostal worship, belief, and embodiment in a therapeutic community: New critical perspectives. *Emot. Space Soc.* **2016**, *19*, 45–55. [CrossRef]
51. Leavey, G. The appreciation of the spiritual in mental illness: A qualitative study of beliefs among clergy in the UK. *Transcult. Psychiatry* **2010**, *47*, 571–590. [CrossRef] [PubMed]
52. Small, H. Co-citation in the scientific literature: A new measure of the relationship between two documents. *J. Am. Soc. Inf. Sci.* **1973**, *24*, 265–269. [CrossRef]
53. Cadman, L. Nonrepresentational Theory/Nonrepresentational Geographies. In *International Encyclopedia of Human Geography*, 1st ed.; Kitchen, R., Thrift, N., Eds.; Elsevier: Oxford, UK, 2009; pp. 456–463.
54. Andrews, G.J.; Chen, S.; Myers, S. The 'taking place'of health and wellbeing: Towards non-representational theory. *Soc. Sci. Med.* **2014**, *108*, 210–222. [CrossRef]
55. Gatrell, A.C. Therapeutic mobilities: Walking and 'steps' to wellbeing and health. *Health Place* **2013**, *22*, 98–106. [CrossRef]
56. Foley, R.; Kistemann, T. Blue space geographies: Enabling health in place. *Health Place* **2015**, *35*, 157–165. [CrossRef] [PubMed]
57. Finlay, J.; Franke, T.; McKay, H.; Sims-Gould, J. Therapeutic landscapes and wellbeing in later life: Impacts of blue and green spaces for older adults. *Health Place* **2015**, *34*, 97–106. [CrossRef] [PubMed]
58. Conradson, D. Spaces of care in the city: The place of a community drop-in centre. *Soc. Cult. Geogr.* **2003**, *4*, 507–525. [CrossRef]
59. Andrews, G.J.; Holmes, D.; Poland, B.; Lehoux, P.; Miller, K.L.; Pringle, D.; McGilton, K.S. 'Airplanes are flying nursing homes': Geographies in the concepts and locales of gerontological nursing practice. *J. Clin. Nurs.* **2005**, *14*, 109–120. [CrossRef] [PubMed]
60. Andrews, G.J. (Re) thinking the dynamics between healthcare and place: Therapeutic geographies in treatment and care practices. *Area* **2004**, *36*, 307–318. [CrossRef]
61. Angus, J.; Kontos, P.; Dyck, I.; McKeever, P.; Poland, B. The personal significance of home: Habitus and the experience of receiving long-term home care. *Sociol. Health Illn.* **2005**, *27*, 161–187. [CrossRef] [PubMed]

62. Poland, B.; Lehoux, P.; Holmes, D.; Andrews, G. How place matters: Unpacking technology and power in health and social care. *Health Soc. Care Community* **2005**, *13*, 170–180. [CrossRef] [PubMed]
63. Hassink, J.; Elings, M.; Zweekhorst, M.; van den Nieuwenhuizen, N.; Smit, A. Care farms in the Netherlands: Attractive empowerment-oriented and strengths-based practices in the community. *Health Place* **2010**, *16*, 423–430. [CrossRef]
64. Hine, R.; Peacock, J.; Pretty, J. Care farming in the UK: Contexts, benefits and links with therapeutic communities. *Ther. Communities* **2008**, *29*, 245–260.
65. Cacciatore, J.; Gorman, R.; Thieleman, K. Evaluating care farming as a means to care for those in trauma and grief. *Health Place* **2020**, *62*, 102281. [CrossRef]
66. Gorman, R. Therapeutic landscapes and non-human animals: The roles and contested positions of animals within care farming assemblages. *Soc. Cult. Geogr.* **2017**, *18*, 315–335. [CrossRef]
67. Milligan, C.; Gatrell, A.; Bingley, A. 'Cultivating health': Therapeutic landscapes and older people in northern England. *Soc. Sci. Med.* **2004**, *58*, 1781–1793. [CrossRef]
68. Gorman, R. Smelling therapeutic landscapes: Embodied encounters within spaces of care farming. *Health Place* **2017**, *47*, 22–28. [CrossRef] [PubMed]
69. Jackson, J.B. *A Sense of Place, A Sense of Time*; Yale University Press: New Haven, CT, USA, 1994.
70. Harrison, S.; Dourish, P. Re-place-ing space: The roles of place and space in collaborative systems. In Proceedings of the 1996 ACM Conference on Computer Supported Cooperative Work, Boston, MA, USA, 16–20 November 1996; pp. 67–76. [CrossRef]
71. Taheri, S.; Sichani, M.G.; Shabani, A. Evaluating the literature of therapeutic landscapes with an emphasis on the search for the dimensions of health: A systematic review. *Soc. Sci. Med.* **2021**, *275*, 113820. [CrossRef] [PubMed]
72. Moon, G. *Health Geography International Encyclopedia of Human Geography*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 315–321.
73. Hong, Z.; Bo, L. Concepts analysis and research implications: Sense of place, place attachment and place identity. *J. South China Norm. Univ.* **2011**, *1*, 1–8.
74. Panelli, R.; Tipa, G. Placing well-being: A Maori case study of cultural and environmental specificity. *EcoHealth* **2007**, *4*, 445–460. [CrossRef]
75. Dunkley, C.M. A therapeutic taskscape: Theorizing place-making, discipline and care at a camp for troubled youth. *Health Place* **2009**, *15*, 88–96. [CrossRef] [PubMed]
76. Lea, J. Retreating to nature: Rethinking 'therapeutic landscapes'. *Area* **2008**, *40*, 90–98. [CrossRef]
77. Masuda, J.R.; Crabtree, A. Environmental justice in the therapeutic inner city. *Health Place* **2010**, *16*, 656–665. [CrossRef] [PubMed]
78. Milligan, C.; Bingley, A. Restorative places or scary spaces? The impact of woodland on the mental well-being of young adults. *Health Place* **2007**, *13*, 799–811. [CrossRef]
79. Hartig, T.; Mitchell, R.; de Vries, S.; Frumkin, H. Nature and Health. *Annu. Rev. Public Health* **2014**, *35*, 207–228. [CrossRef] [PubMed]
80. Keniger, L.; Gaston, K.; Irvine, K.; Fuller, R. What are the Benefits of Interacting with Nature? *Int. J. Environ. Res. Public Health* **2013**, *10*, 913–935. [CrossRef] [PubMed]
81. Abraham, A.; Sommerhalder, K.; Abel, T. Landscape and well-being: A scoping study on the health-promoting impact of outdoor environments. *Int. J. Public Health* **2010**, *55*, 59–69. [CrossRef] [PubMed]
82. Kemperman, A.; Timmermans, H. Green spaces in the direct living environment and social contacts of the aging population. *Landsc. Urban Plan.* **2014**, *129*, 44–54. [CrossRef]
83. Andreucci, M.B.; Russo, A.; Olszewska-Guizzo, A. Designing urban green blue infrastructure for mental health and elderly wellbeing. *Sustainability* **2019**, *11*, 6425. [CrossRef]
84. Rodiek, S.; Nejati, A.; Bardenhagen, E.; Lee, C.; Senes, G. The seniors' outdoor survey: An observational tool for assessing outdoor environments at long-term care settings. *Gerontologist* **2016**, *56*, 222–233. [CrossRef] [PubMed]
85. Tharrey, M.; Darmon, N. Urban collective garden participation and health: A systematic literature review of potential benefits for free-living adults. *Nutr. Rev.* **2022**, *80*, 6–21. [CrossRef] [PubMed]
86. Jiang, S. Therapeutic landscapes and healing gardens: A review of Chinese literature in relation to the studies in western countries. *Front. Archit. Res.* **2014**, *3*, 141–153. [CrossRef]
87. Soga, M.; Gaston, K.J.; Yamaura, Y. Gardening is beneficial for health: A meta-analysis. *Prev. Med. Rep.* **2017**, *5*, 92–99. [CrossRef]
88. Cipriani, J.; Benz, A.; Holmgren, A.; Kinter, D.; McGarry, J.; Rufino, G. A systematic review of the effects of horticultural therapy on persons with mental health conditions. *Occup. Ther. Ment. Health* **2017**, *33*, 47–69. [CrossRef]
89. Wilson, K. Therapeutic landscapes and First Nations peoples: An exploration of culture. *Health Place* **2003**, *9*, 83–93. [CrossRef]
90. Conradson, D. Landscape, care and the relational self: Therapeutic encounters in rural England. *Health Place* **2005**, *11*, 337–348. [CrossRef]
91. Schmidt, T.; Pawlowski, C.S.; Kerr, J.; Schipperijn, J. Investigating the WHAT and WHY on older adults' use of neighborhood open spaces following an environmental intervention. *Transl. Behav. Med.* **2021**, *11*, 582–596. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

buildings

MDPI

*Article*

# Spatial Feature Analysis of the Beijing Forbidden City and the Shenyang Imperial Palace Based on Space Syntax

**Dongxu Zhang [1], Xuyang Shan [2], Xinyi Zhang [1], Hao Chen [1] and Yingsheng Zheng [1,*]**

[1] School of Architecture and Urban Planning, Guangzhou University, Guangzhou 510006, China; zhangdongxu@gzhu.edu.cn (D.Z.); 2112209013@e.gzhu.edu.cn (X.Z.); 2112209006@e.gzhu.edu.cn (H.C.)
[2] College of Arts, Northeastern University, Shenyang 110819, China; shanxuyang96@163.com
* Correspondence: zhengyingsheng@gzhu.edu.cn

**Abstract:** As two of the most complete existing examples of royal architecture and cultural World Heritage Sites in China, the Beijing Forbidden City and the Shenyang Imperial Palace are distinctive in terms of their spatial organization. This study used the relational diagram method of space syntax theory to quantitatively analyze the spaces of these two palaces. Furthermore, the characteristics of these spaces were explored by comparing the integration and depth value of each palace space, as well as the differences in architectural culture between the different times and nationalities that they reflect. The results show that in the Forbidden City, office space had the lowest degree of spatial enclosure (depth value), while living space had the highest spatial enclosure. Moreover, there was little difference in accessibility (integration value) among office space, living space, and recreation space. In the Shenyang Imperial Palace, the accessibility of office space, living space, and recreation space showed a decreasing trend, while their spatial enclosure showed an increasing trend. The depth values of office space, living space, and recreation space were higher in the Beijing Forbidden City than in the Shenyang Imperial Palace by 245%, 109%, and 35%, respectively. The integration value of office space was 22.2% higher in the Shenyang Imperial Palace than in the Forbidden City, while the integration values of living space and recreation space were higher in the Forbidden City than in the Shenyang Imperial Palace by 13.9% and 49.2%, respectively. The degree of enclosure of the recreation spaces in both palaces was very strong, indicating that the royal family paid attention to privacy during their leisure activities. In the process of use, the functional conversion of different palaces in the Forbidden City significantly improved the accessibility of both the emperor's living space and the minister's office space and simultaneously strengthened the connection between these two spaces. Factors in the construction sequence led to the unreasonable accessibility of recreation space in the Shenyang Imperial Palace.

**Keywords:** Forbidden City; Shenyang Imperial Palace; space syntax theory; spatial feature; relational diagram method

**Citation:** Zhang, D.; Shan, X.; Zhang, X.; Chen, H.; Zheng, Y. Spatial Feature Analysis of the Beijing Forbidden City and the Shenyang Imperial Palace Based on Space Syntax. *Buildings* **2023**, *13*, 2615. https://doi.org/10.3390/buildings13102615

Academic Editor: Haifeng Liao

Received: 10 September 2023
Revised: 6 October 2023
Accepted: 10 October 2023
Published: 17 October 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

As cultural World Heritage Sites, the Forbidden City in Beijing and the Shenyang Imperial Palace are two of the best-preserved ancient palaces in China. The Forbidden City was constructed between 1406 and 1420 by Zhu Di, an emperor of the Ming dynasty (1368–1644). It is the largest existing palace complex in the world. The Shenyang Imperial Palace is located in the northeast region of China and was built by the early rulers of the Qing dynasty (1644–1911) in 1625, followed by continuous construction by several emperors. After the ruler of the Qing dynasty overthrew the emperor of the Ming dynasty and moved into the Forbidden City in 1644, the Shenyang Imperial Palace became the emperor's largest holiday palace, located outside of Beijing. The architecture of the Shenyang Imperial Palace has strong Manchu ethnic characteristics. The two palaces differ in their spatial form due

to differences in the builders' ethnic and cultural backgrounds, regional conditions, and construction techniques.

Scholars have conducted studies on the architecture of the two palaces. For the Beijing Forbidden City, Yu systematically introduced the technology and art of traditional Chinese architecture and synthesized the architectural art of the Forbidden City in terms of its construction history, planning, and design ideas [1]. Bai and Huang pointed out that the royal palaces were the sites where the monarchs lived and exercised their autocratic kingship and were also centers of state power. These authors discussed the architectural embodiment of the concept of the supremacy of the monarchy [2]. For the Shenyang Imperial Palace, Wu studied the architectural layout and decorative art [3], while Chen and Wang emphasized that different architectural characteristics reflected different political and economic backgrounds, highlighting the important role of the political and economic context in the formation of architecture through an analysis of the architecture of the Shenyang Imperial Palace [4]. Luo discussed the culture of the Shenyang Imperial Palace in three different architectural developmental stages, presenting clear cultural development and describing the basic trend of development of Manchu national culture [5]. In general, current research on the architectural spaces of the two palaces is mainly qualitative in nature and lacks quantitative analysis of the related spatial features. No study has analyzed the correspondence between palace space and use functions, which means that no previous study has accurately compared the similarities and differences between the two palace spaces.

Space syntax quantifies and evaluates the spatial form of human settlements, including buildings, cities, and even landscapes, by treating space as an independent element. This approach can analyze the relationship between spaces at different scales and reveal the internal correlation between human activity patterns and spatial structure [6,7], explain human behavior and social activities from the perspective of spatial configuration [8,9], and even make distinctive contributions to research in social and urban history [10]. Social factors also influence the production of space, creating foreground spaces that extend beyond the local and background spaces that are more supportive of local communities [11]. Yamu et al. provided a holistic and compact overview of the various concepts used in space syntax, from their basic elements to analytical techniques and theories [12]. Currently, space syntax theory is widely used in quantitative studies of various types of space, such as medical space [13], traditional village space [14], urban underground space [15], urban block space [16], urban park space [17], and historical city space [18]. This approach has also been applied in the study of palace building space worldwide. Nevadomsky used space syntax theory to conduct a quantitative analysis of the sites within Ogiamien's palace and the chiefdom of other Benin kingdoms and compared the results using qualitative analysis to confirm the traditional social nature of the use of space in the chiefdom of the former kingdom [19]. Baumanova and Smejda studied the palace building space on the Gede site near the coast of Kenya and found that the configuration and use of rooms in the palace, their position in the communication network, and the social and cultural content of the space changed with time [20]. Eyal Regev's study of Herodian palaces explored social relationships at court and showed that social interactions in the palace were hierarchical, emphasizing the privacy of the king and his control over the interactions of potential visitors [21]. These studies show that space syntax not only provides a scientific basis for the quantitative analysis of the intricate spatial organization within palace complexes but also allows for consideration of the interactions between the function of the architectural spaces and the social and cultural activities that occurred within these spaces. However, the spatial differences between Chinese and Western palaces make it difficult to directly apply or refer to relevant Western research results. To date, relatively little academic research uses the space syntax approach with regard to Chinese palace spaces. Only Zhu has used the space syntax method to quantitatively analyze and confirm that the Forbidden City was the highest-ranked, most enclosed, and most inaccessible part of Beijing City [22]. However, in Zhu's study, there is a lack of corresponding analysis of the traditional architectural and cultural differences behind the spatial features and no

comparison of the spatial organization of the Beijing Forbidden City with similar domestic or foreign royal palaces.

This paper aims to quantitatively analyze the spatial features of the Beijing Forbidden City and the Shenyang Imperial Palace, as well as the similarities and differences between them. First, the relational diagram method of space syntax theory is used to obtain the integration and depth values of various spaces in the two palaces in Beijing and Shenyang. Then, the differences in spatial organization characteristics reflected by these two values are compared. Finally, this study makes a spatial comparison between traditional Chinese and Western palaces to explore the role of power, the ritual system, hierarchy, and other factors in the evolution of spatial form and function. This paper uses space syntax for the analysis of these two traditional Chinese palaces, which not only expands the research object of spatial syntax and clarifies the spatial characteristics of ancient Chinese palace buildings but can also inform the design of similar modern group buildings.

## 2. Research Methods

### *2.1. Spatial Layout of the Forbidden City and the Shenyang Imperial Palace*

The Forbidden City, which is located in the center of Beijing, has a length of 961 m from north to south and a width of 753 m from east to west. It covers an area of approximately 725,000 square meters and a building area of 150,000 square meters (Figure 1a). Its axis coincides with the city's central axis, and it is basically symmetrical along the north–south axis according to the principle of "office space in the front area and living space in the back area". It is an important example of the integration of architectural art and technology in ancient Chinese palaces. To reflect the legitimate position of the emperor and the will of the ruling class, the planning and architectural design of the Forbidden City are emphasized in a hierarchical and modular layout to highlight the concept of imperial power with additional attention to the ritual system and order.

The office space is located in the southern part of the Forbidden City, with the Hall of Supreme Harmony (numbered Beijing Office Space-1, hereinafter referred to as BOS-1), the Hall of Central Harmony (BOS-2), and the Hall of Preserving Harmony (BOS-3) positioned at the center (Figure 1b). The office space is where the emperor managed government affairs and held large-scale ceremonies; therefore, it reflects the highest architectural level and grandeur to represent the authority of imperial power. The smaller Hall of Civil Glory (BOS-4) and Hall of Martial Grace (BOS-5) are symmetrically arranged on opposite sides of the office space. Neige Hall (BOS-6), located in the southernmost part of the office space, and Junji Hall (BOS-7), located near the living space, were usually used by ministers to address government affairs. The royal living space is located in the northern part of the Forbidden City with three important palaces arranged on the main axis, namely, the Palace of Heavenly Purity (Beijing Living Space-1, or BLS-1), the Hall of Union (BLS-2), and the Palace of Earthly Tranquility (BLS-3). These are the main palaces where the emperors and empresses lived. The Palace of Mental Cultivation (BLS-4) was the residence chosen by the emperor in the middle and late Qing dynasties. The Palace of Eternal Harmony (BLS-5) located on the east side and the Palace of Lasting Spring (BLS-6) located on the west side were the palaces where the emperor's wives resided, and the Northern Five Abodes (BLS-7) were the residences of the princes; thus, the building scale is relatively small. The recreation space is located on the east side of the living space (Figure 1) and mainly includes the Hall of Imperial Supremacy (Beijing Recreation Space-1, BRS-1), the Hall of Spiritual Cultivation (BRS-2), Changyinge Theatre (BRS-3), and the Imperial Garden (BRS-4).

Construction of the Shenyang Imperial Palace began in 1625, and two large-scale additions were subsequently built. As shown in Figure 2a, the spatial pattern forms three relatively independent groups of palace buildings with parallel longitudinal axes (East Road, Middle Road, and West Road palaces). The palace covers an area of 60,000 square meters and consists of over 500 rooms. The earliest East Road palaces (built in 1625) reflected the political characteristics of the military and political unity of the Manchu nomads; thus, the spatial layout did not adopt the traditional Chinese courtyard style and

did not model the ritual system [23]. With the deepening influence of Han culture on the Qing dynasty, the Middle Road palaces (built from 1627 to 1635) and the West Road palaces (built starting in 1781) adopted the traditional courtyard layout of China, maintaining the Manchu ethnic characteristics only in architectural details. Thus, the style of ethnic integration was more evident in these structures [24].

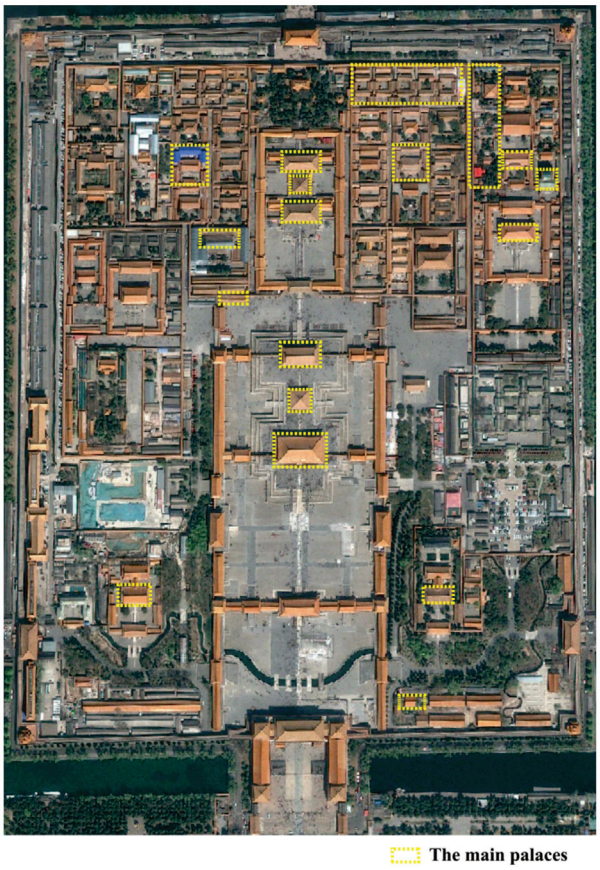
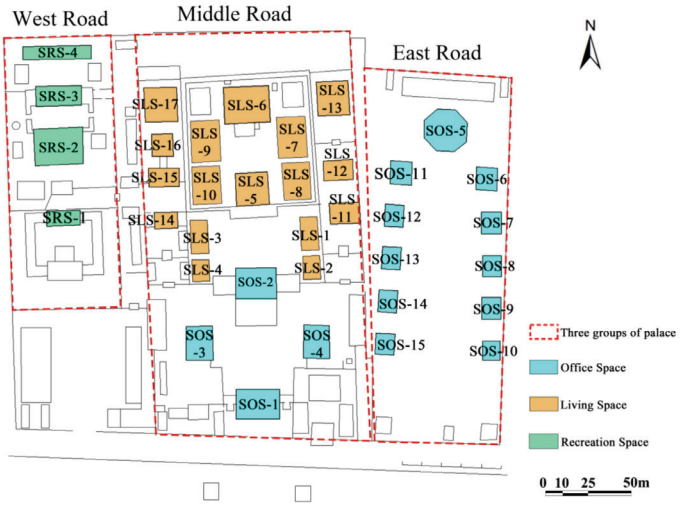



**Figure 1.** The map of the Beijing Forbidden City: (**a**). Aerial view of the Beijing Forbidden City; (**b**). The main space of the Beijing Forbidden City.

(**a**)




(**b**)

**Figure 2.** The map of the Shenyang Imperial Palace: (**a**). Aerial view of the Shenyang Imperial Palace; (**b**). The main space of the Shenyang Imperial Palace.

The office space is located in two areas. All of the East Road palaces are office buildings. As shown in Figure 2b, 10 small palaces (SOS-6 to SOS-15) are arranged symmetrically on both sides, centered on Dazheng Hall (SOS-5) on the north side. They were the places where celebrations, feasts, and other ceremonies were held in the early Qing dynasty. The southern portion of the Middle Road palaces was used as office space during the next period. At the southernmost end of the Middle Road palaces is the Daqing Gate (Shenyang Office Space-1, hereinafter referred to as SOS-1), which was the main entrance of the Shenyang Imperial Palace. Chongzheng Hall (SOS-2), located on the north side of the Daqing Gate on the central axis, was the most important main hall for the emperor's office in the Shenyang Imperial Palace. Two relatively low secondary office buildings, namely, Xiangfeng Pavilion (SOS-3) and Feilong Pavilion (SOS-4), were symmetrically arranged on either side of the central axis.

The living space is located in the central and northern parts of the Middle Road palaces, with the Xiaqi (Shenyang Living Space-1, SLS-1), Xiezhong Zhai (SLS-2), Rihua (SLS-3), and Shishan Zhai (SLS-4) buildings serving as educational venues for the emperor's children. The Phoenix Building (SLS-5), which is located behind the above-mentioned buildings, is a gate building that connects the front buildings and the five palaces in which the emperors and empresses lived on a high platform. Among them, the Qingning Palace (SLS-6), which is located in the center at the rear, served as the sleeping quarters of early Qing emperors and empresses. The other four important palaces for imperial concubines, namely, Yandu Palace (SLS-7), Guanju Palace (SLS-8), Linzhi Palace (SLS-9), and Yongfu Palace (SLS-10), are arranged on both sides of the central axis (Figure 2b). The palace groups for the emperor's mother and daughters are collectively known as Dong House, including the three houses numbered SLS-11, SLS-12, and SLS-13, while the palace groups for the emperor and his concubines during the late Qing dynasty are collectively called Xi House, including SLS-14, SLS-15, SLS-16, and SLS-17. The recreation space, which was constructed last, is located in the West Road palaces (Figure 2b) and has a courtyard layout, including the Royal Theatre Jiayin Hall (Shenyang Recreation Space-1, SRS-1), the Royal Library Wensu Pavilion (SRS-2), Yangxi Hall (SRS-3), and Jiujian Hall (SRS-4) as imperial study rooms.

### *2.2. Diagram Methods and Processes*

This study used the relational diagram approach of the space syntax method to quantitatively analyze the space of the two palaces located in Beijing and Shenyang. The core concept of space syntax is configuration, which is defined as a series of interdependent relationships among parts, each of which is determined by the relationship between a certain part and all the others. In our study, the buildings and courtyards are abstractly divided to form a relational diagram that reflects the spatial configuration, and a relational diagram (J-Graph) is formed using the external space as the root space. The quantitative description of space reveals the relationships among the internal organizational logic of space, human behavior, and social culture [6,25]. For spatial morphological analysis, space syntax provides a series of spatial attribute parameters [8]. The main spatial variables used in this study are the depth value and the integration value. The depth value reflects the number of spatial transformations in the system. The more conversions there are from one space to another, the greater the depth of the space is; thus, this space appears more hidden in the entire system, and the degree of enclosure of the space is higher. In contrast, the lower the depth value of the space, the more open it appears. The integration value reflects the traffic potential of a space. The higher the integration value, the stronger the accessibility of the space. In contrast, the lower the integration, the worse the accessibility. Notably, the depth value selected in this paper is the step depth that is calculated from the main entrance of the street connecting the palace to the outside. It reflects the degree of external connection of this space in the palace, while the integration value reflects the transportation accessibility of the internal space system in the palace.

In our study, first the various spaces of the Forbidden City and the Shenyang Imperial Palace were numbered (Figure 3), and spatial connections were made based on the transformation of space, with points representing the spaces and lines representing the connections between these spaces. Then, the entire spatial system was transformed into a J-Graph plot using an external space as the starting point. These rooms were arranged horizontally according to the depth of their spatial structure [26], as shown in Figure 4a,b. Finally, the depth value and integration value of each space were determined.

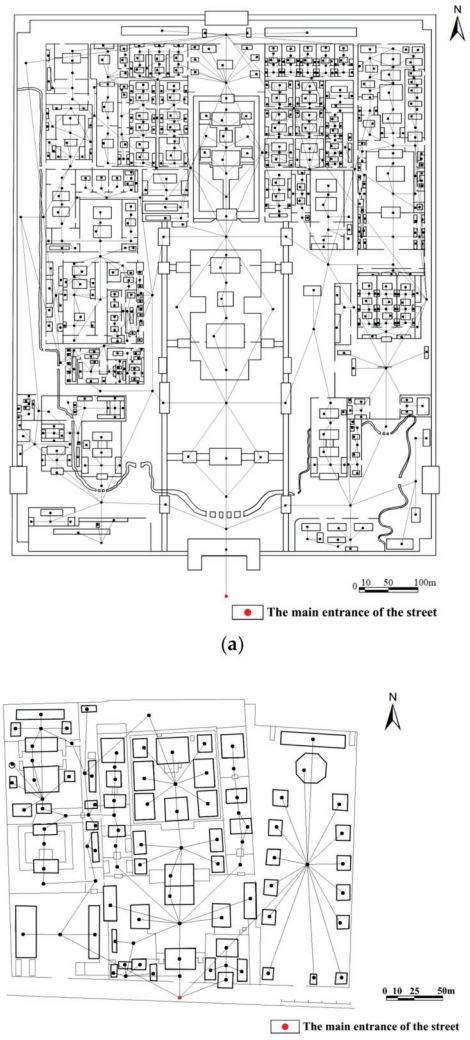



**Figure 3.** Space-numbering map: (**a**). The Forbidden City; (**b**). The Shenyang Imperial Palace.

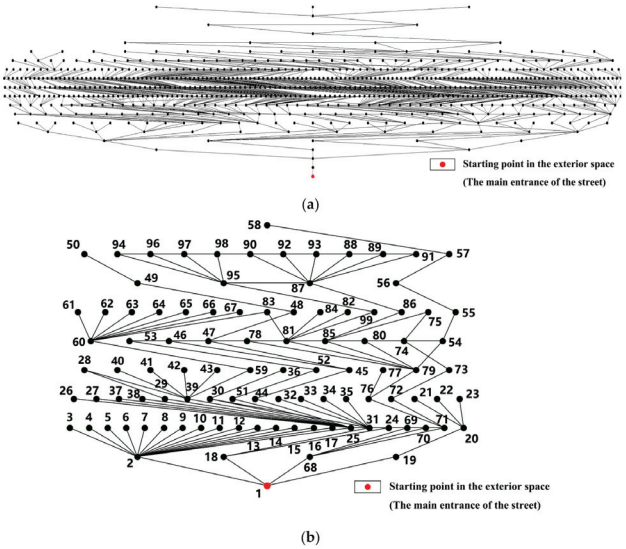



**Figure 4.** J-Graph of the Two Palaces: (**a**). The Forbidden City (**b**). The Shenyang Imperial Palace.

## 3. Results

### *3.1. Results of the Beijing Forbidden City*

The enclosure (depth value) and accessibility (integration value) of the office space, living space, and recreation space in the Forbidden City were analyzed. In terms of depth (as shown in Table 1), the three most important halls in the office space (BOS-1, BOS-2, and BOS-3) had an average depth of 8. The two symmetrical secondary palaces (BOS-5 and BOS-4), which functioned as spaces for small-scale ceremonies held by the emperor, had an average depth of 6.5. BOS-6 in the southeast and BOS-7 in the northwest were the main office locations for ministers during the Ming and Qing dynasties and served to communicate information between the office space in the front and the living space in the rear. Both locations had a depth of 8. Overall, the depth of the office space in the Forbidden City ranged from 6 to 9, and the average depth of the main living space in the Forbidden City was 11.7. BLS-1, BLS-2, and BLS-3, which served as the main bedchambers of the emperor and empress, had an average depth of 11.3. BLS-4, which had a certain office function, had a minimum depth of 10. The average depth of the concubine residences (BLS-5 and BLS-6) was 12. BLS-7, where the princes lived, had a maximum depth value of 14. The depth values of the four recreation spaces ranged between 9 and 12, with a mean of 10.8. Among the three types of spaces, the living space had the greatest depth and the strongest degree of enclosure, which met the requirement for the privacy of royal life. However, the recreation space in the Forbidden City was more enclosed than the office space, indicating that royal leisure and entertainment in China also required privacy and were not shared with others.

**Table 1.** Depth and integration values in the Beijing Forbidden City.

| **Code** | **BOS-1** | **BOS-2** | **BOS-3** | **BOS-4** | **BOS-5** | **BOS-6** | **BOS-7** | **BRS-1** | **BRS-2** |
|---|---|---|---|---|---|---|---|---|---|
| Depth | 7 | 8 | 9 | 6 | 7 | 8 | 8 | 12 | 11 |
| Integration | 0.90 | 0.93 | 1.05 | 0.82 | 0.74 | 0.65 | 1.23 | 0.92 | 0.85 |
| **Code** | **BLS-1** | **BLS-2** | **BLS-3** | **BLS-4** | **BLS-5** | **BLS-6** | **BLS-7** | **BRS-3** | **BRS-4** |
| Depth | 11 | 11 | 12 | 10 | 13 | 11 | 14 | 9 | 11 |
| Integration | 0.95 | 0.95 | 0.92 | 1.00 | 0.80 | 0.90 | 0.78 | 1.02 | 0.95 |

The integration values of various spaces in the Forbidden City are shown in Table 1. The average value for the office space was 0.90. As the main office spaces for the emperor in the Forbidden City, the average integration of the three halls (BOS-1, BOS-2, and BOS-3) was 0.96, showing a relatively high level of accessibility. The office space (BOS-7) used by ministers in the late Qing dynasty had the highest accessibility level (with an integration value of 1.23), while the accessibility level of BOS-6, which was used by ministers in the early Qing dynasty, was the lowest (0.65). The integration level of BOS-4, which is located east of the central axis of the Forbidden City, was 0.82, while the integration level of BOS-5 in the west was 0.74. The overall integration level was high in the east and low in the west (Figure 5). This result shows that although the buildings in the Forbidden City are basically symmetrically arranged along the central axis, accessibility has an asymmetric spatial layout. Regarding the order of the integration values within the living space, the emperor's residences (BLS-1, BLS-2, and BLS-3, with an average of 0.94) were first, followed by the concubines' residences (BLS-5 and BLS-6, with an average of 0.85) and the princes' residences (BLS-7's integration value was 0.78); these results indicate that the accessibility of the living spaces of the concubines and princes was lower than that of the emperor's palaces, which could have highlighted the central position of the emperor while protecting the privacy of the lives of the concubines and princes. The average integration level of the recreation space was 0.94, among which BRS-3 (a theater) had the greatest integration (1.02) and accessibility levels, basically meeting the requirements of its performance function. Overall, there was little difference among the average integration values of the three types of spaces in the Forbidden City; however, the integration of each palace differed significantly according to the needs of different users.

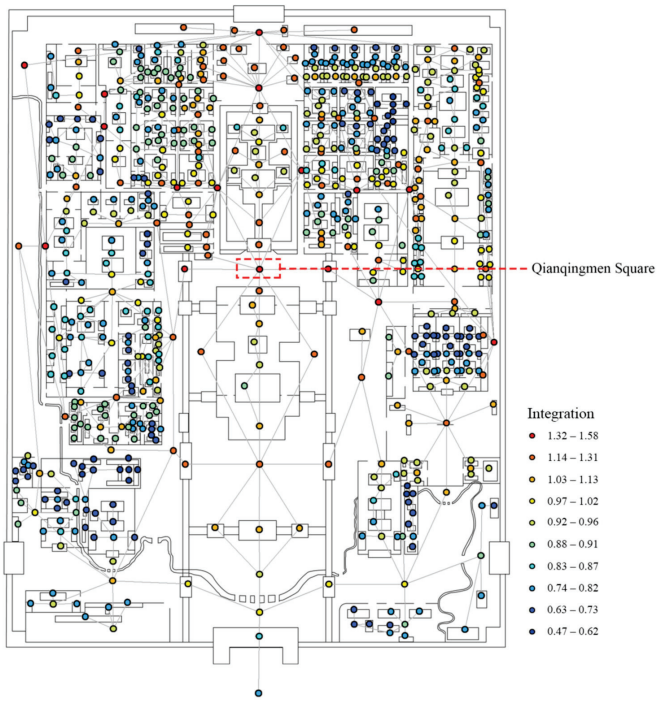



**Figure 5.** The integration value classification map of the Forbidden City.

### *3.2. Results of the Shenyang Imperial Palace*

The depth values of various palaces in the Shenyang Imperial Palace are shown in Table 2. The depth of the office space ranged from 2 to 3, with an average of only 2.2, showing that the office space was open while the degree of enclosure was weak. The depth of the living space ranged from 4 to 9, with an average of 5.6. The four palaces where the princes were educated, namely, SLS-(1–4), had a depth of 4, and the space was relatively open. The depth values of palaces SLS-(6–10), where the emperor lived in the early Qing dynasty, were all 6; the average depth of the three palaces (SLS-(11–13)) in the Dong House, where the emperor's mother and children lived, was 6.3; and the average depth of the four palaces (SLS-(14–17)) in the Xi House, where the emperor lived in the late Qing dynasty, was 6.8, indicating the highest degree of spatial enclosure in the living space. The average depth of the recreation space was 8, and the degree of enclosure was the greatest in the Shenyang Imperial Palace.

**Table 2.** Depth and integration values in the Shenyang Imperial Palace.

| **Code** | **SOS -1** | **SOS -2** | **SOS -3** | **SOS -4** | **SOS -5** | **SOS -(6–15)** | | **SRS -1** | **SRS -2** | **SRS -3** | **SRS -4** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth | 2 | 3 | 3 | 3 | 2 | 2 | | 6 | 8 | 9 | 9 |
| Integration | 1.65 | 1.19 | 1.18 | 1.18 | 1.03 | 1.03 | | 0.81 | 0.62 | 0.55 | 0.55 |
| **Code** | **SLS -(1–4)** | **SLS -5** | **SLS -6** | **SLS -(7–10)** | **SLS -11** | **SLS -12** | **SLS -13** | **SLS -14** | **SLS -15** | **SLS -16** | **SLS -17** |
| Depth | 4 | 4 | 6 | 6 | 5 | 6 | 8 | 5 | 6 | 7 | 9 |
| Integration | 0.98 | 1.03 | 0.70 | 0.70 | 0.79 | 0.67 | 0.51 | 1.00 | 0.78 | 0.66 | 0.50 |

In terms of integration, the average integration value of the office space was 1.10. The integration value of SOS-1, which references the gate of the Middle Road palaces, was 1.65, making it the space with the highest level of accessibility in the Shenyang Imperial Palace. The integration values of SOS-2, which references the main hall on the Middle Road, and of the two palaces on either side of it (SOS-3 and SOS-4) were very close, with an average of 1.18. The integration values of SOS-5, which is the main hall on the East Road, and of the ten secondary palaces SOS-(6–11) on either side of it were all 1.03, marking the lowest level of accessibility in the office space. The average integration value

of the living space was 0.79; the integration value of SLS-5, which mainly played a role in transportation, was 1.03, marking the highest level of accessibility in the living space. The average integration value of SLS-(1–4), which was used for the imperial children's education, was similar at 0.98. The average integration value of SLS-(6–10), which references the palaces where the emperor lived before the establishment of the Qing dynasty in 1644, was 0.70. The average integration value of the four palaces in the Xi House (SLS-(14–17)), where the emperor lived in the late Qing dynasty, was 0.74. The average integration value of the three palaces in Dong House (SLS-(11–13)), where the emperor's mother and children lived, was 0.66, which marked the lowest level of spatial accessibility. In the recreation space (as shown in Table 2), the integration value of the Jiayintang Theater performance building (SRS-1) was relatively high at 0.81, while the average integration value of the remaining three recreation spaces was only 0.57, which indicated a lower level of accessibility. The results indicate that the emperor's leisure activities were kept highly private. The distribution of integration in the Shenyang Imperial Palace is shown in Figure 6.

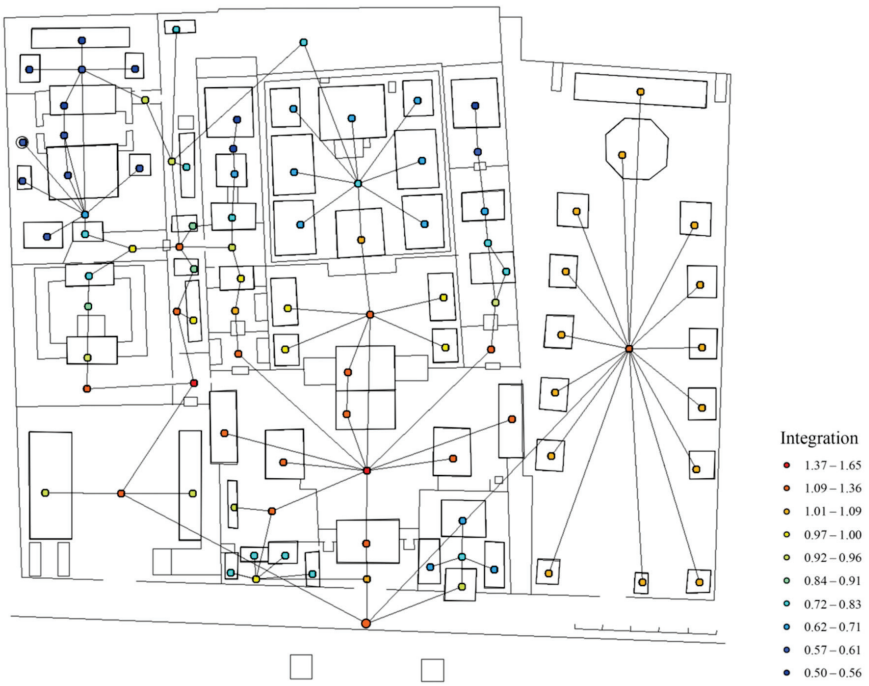



**Figure 6.** The integration value classification map of the Shenyang Imperial Palace.

## 4. Discussion

### *4.1. Comparison between the Two Palaces*

In the office space, as shown in Figure 7a, the average depth of the emperor's three main office spaces in the Beijing Forbidden City (BOS-(1–3)) was 8 (the average integration value was 0.96), while the average depth of the emperor's two main office spaces (SOS-2 and SOS-5) in the Shenyang Imperial Palace was 2.5 (the average integration value was 1.11). These results indicated that the emperor's office space in the Forbidden City was relatively enclosed, while the emperor's office space in the Shenyang Imperial Palace had a relatively high level of accessibility. This might be because the layout of the Beijing Forbidden City was more complex and emphasized architectural hierarchy through a higher degree of enclosure. As the Shenyang Imperial Palace was an early palace, its layout was relatively simple, and the concept of hierarchy was not prominent; rather, convenient transportation and the equal relationship between the emperor's office space and other spaces were emphasized. Previous studies have shown that the more centrally an object is placed within a defined space, the more it contributes to the overall segregation of that particular space. A building that is placed in the middle of a central square adds greater

overall segregation to the neighborhood than the same building that is placed at the edge of the square [12]. From this perspective, compared to the Shenyang Imperial Palace, the emperor's three main office spaces in the Forbidden City in Beijing were located more centrally, making a more prominent contribution to spatial segmentation.

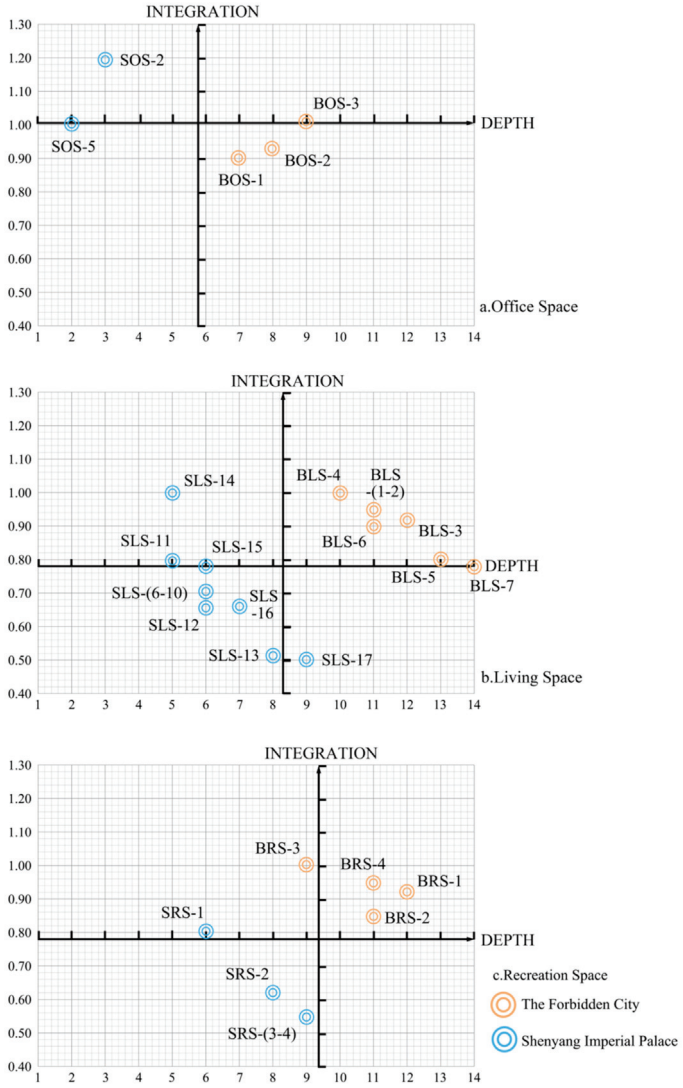



**Figure 7.** Comparison of the spatial enclosure and accessibility of the different spaces.

In terms of the living space, as shown in Figure 7b, in the Forbidden City, the average depth value of the emperor's three main bedchambers (BLS-(1–3)) was 11.3 (with an average integration value of 0.94), while the average depth of the concubines' bedchambers (BLS-(5–6)) was 12 (with an average integration value of 0.85). In the Shenyang Imperial Palace, the depths of the emperor's main bedchamber (SLS-6) and the concubines' bedchambers (SLS-(7–10)) were all 6 (the integration values were all 0.70), which were much lower than the values for the emperor's three main bedchambers in the Forbidden City. These results indicate that the enclosure of the bedchambers in the Forbidden City was significantly higher than that of the corresponding bedchambers in the Shenyang Imperial Palace.

In addition, the integration value (accessibility) of the emperor's bedchamber (SLS-6) was the same as that of the concubines' bedchambers (SLS-(7–10)) in the Shenyang Imperial Palace, reflecting a strong level of equality. The concept of hierarchy in traditional Chinese Confucian culture was not reflected in these spaces in the Shenyang Imperial Palace. The average integration of the emperor's bedchambers (BLS-(1–3)) was higher than

that of the concubines' bedchambers (BLS-(5–6)) in the Forbidden City, which suggests that their accessibility level was higher. These results indicate an obvious hierarchical concept between these spaces.

As shown in Figure 7c, the average depth of the four recreation spaces in the Forbidden City was 10.8 (the average integration value was 0.94), while the average depth of the four recreation spaces in the Shenyang Imperial Palace was 8 (the average integration value was 0.63). Thus, the recreation space in the Forbidden City of Beijing had a higher degree of enclosure than the recreation space in the Shenyang Imperial Palace in terms of connection with external spaces and had greater accessibility, which showed that the internal transportation was more convenient.

The average depth and integration values between the various spaces of the two palaces are shown in Figure 8. The degree of enclosure of the living space, the recreation space, and the office space presented a decreasing trend in sequence in the Forbidden City, while the level of accessibility showed little difference. In the Shenyang Imperial Palace, the degree of spatial enclosure of the recreation space, the living space, and the office space decreased, while the level of accessibility increased sequentially. In both palace groups, the office space had the lowest degree of enclosure, which was in line with its functional requirements. The entirety of the Forbidden City was built at the same time after unified planning sessions; thus, it is reasonable that the degree of spatial enclosure of the recreation space was lower than (accessibility was higher than) that of the living space, which necessitated relative privacy. The construction of the Shenyang Imperial Palace was divided into three phases and completed gradually. The level of importance of the recreation space was lower than that of the office and living spaces; thus, it was the last space to be built. There was a certain irrationality in the location setting, which led to the degree of spatial enclosure of the recreation space being higher than that of the living space (the level of accessibility being lower than that of the living space).

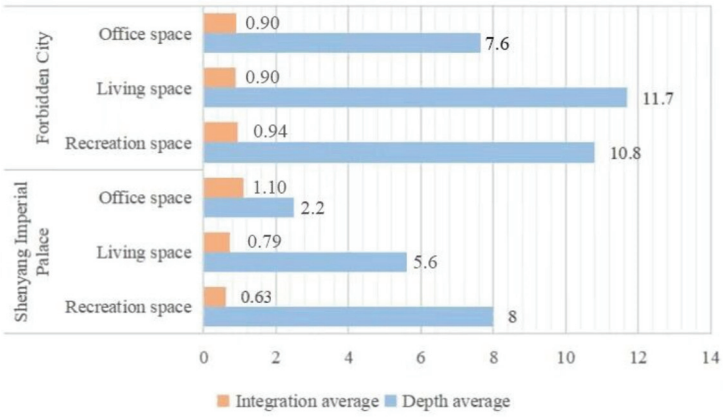



**Figure 8.** The parameter average of the different spaces in the two palaces.

### *4.2. Changes in Spatial Organization and Function*

Social structuring with an unfixed rank is a method of studying political organization [27]. There is a connection between space and power levels; thus, previous research has attempted to understand both power levels in the context of space [28,29] and how spatial organizational practices have shaped the essence of political levels in architecture [30,31]. In the two Chinese traditional palace groups that emphasized imperial power, the development and changes of these spatial organizations and functions should therefore be considered.

(1) Historically, the function of many spaces in the Forbidden City changed. For example, in the late Qing dynasty, the emperor moved his bedchambers from the original palaces (BLS-(1–3)) to BLS-4 (the depth value decreased from 11.3 to 10, while the integration value increased from 0.94 to 1.00). The spatial enclosure and accessibility changed slightly. At the same time, the most important office space for the main ministers was transferred from BOS-6 to BOS-7 (while the depth was unchanged, the integration

increased from 0.65 to 1.23). The original office space group of BOS-(1–3) used by the emperor and BOS-6 used by the ministers was shifted backward as a whole to form a new "administrative power center" dominated by BLS-4 and BOS-7. This change improved the accessibility of the ministers' office space and strengthened the connection between the emperor's living space and the ministers' office space, which could have improved the emperor's efficiency in handling government affairs. However, it could also have placed the emperor and ministers farther from the external environment, which might have led to a decrease in the importance attached by the rulers to the people.

In the Shenyang Imperial Palace, when the emperor's office spaces were transferred from the East Road to the Middle Road, the average depth increased from 2 to 2.8 and the spatial enclosure was enhanced. These changes were conducive to the formation of a sense of imperial authority and dignity. At the same time, the average integration value increased from 1.03 to 1.30, the level of accessibility improved, and internal transportation connections became more convenient. In terms of increasing integration values, the conversion of office space for emperors in the Shenyang Imperial Palace was similar to the conversion of office space for emperors and ministers in the Forbidden City of Beijing, which was also very similar to the conversion of the royal office space in Seoul in the seventeenth century. The new site of the top administrative headquarters of the Joseon Dynasty, that is, the king's palaces and government headquarters, was placed in the site that had integration values higher than those for other areas [32].

(2) The construction sequence of the Shenyang Imperial Palace was East Road, then Middle Road, and finally West Road. The average depth values of the East Road, Middle Road, and West Road palaces were 2, 5.1 and 8, respectively, while the average integration values were 1.03, 0.88, and 0.63, respectively, indicating that the degree of spatial enclosure of the three groups gradually increased and the accessibility level gradually decreased according to the construction period.

The earliest East Road palace buildings were all office buildings, and the integration values of SOS-(6–15) and SOS-5 were all 1.03. There was no distinction with regard to accessibility, and the space reflected equality. This was likely because before the establishment of the Qing dynasty in 1644, the Manchu regime was composed of various tribes without any thought or consciousness of imperial supremacy; thus, there was no strict hierarchical concept in the architectural space. Therefore, the East Road buildings had the greatest level of accessibility and the greatest amount of open space. In the subsequent construction of the Middle Road palaces, the office space in the south and the living space in the north were symmetrically distributed around the axes formed by SOS-1, SOS-2, SLS-5, and SLS-6, which was in line with the traditional Chinese courtyard layout. The average accessibility value of the Middle Road palaces decreased compared to the East Road palaces. The last construction of the west road building was the least accessible, which was the same as the phased construction of some traditional Chinese villages, and the last construction house for non-primary surname and non-major surname families was often distributed in areas with poor accessibility [14].

### *4.3. Comparison between Traditional Chinese Palaces and Western Palaces*

In the Forbidden City and Shenyang Imperial Palace, the office space was generally located near the main entrance of the palace groups in the south, while the living space was located in the north. The accessibility of the office space was higher than that of the living space. The Topkapu Palace in the Ottoman Empire also had a spatial pattern similar to that of "office space in the front and living space in the rear". This palace placed the center of accessibility in the front office space. However, the spatial development of the Topkapu Palace differed from that of Chinese palaces in regard to improving the accessibility of the backyard and strengthening the rights of women [33]. In three palaces built at different locations in three stages of Herod's empire, the average depth of the palace built in the first stage was between 4 and 5. The king placed great emphasis on the status of the royal family and had limited contact with outside visitors. The average depth of the palace

built in the second stage was reduced to between 2 and 3, which strengthened the level of communication and interaction between the king and officials. Finally, the average depth of the palace in the third stage increased to between 6 and 7, reemphasizing the uniqueness of the king's space [21]. These depth changes repeated in different stages did not appear in the development of the two above-mentioned Chinese palaces. In addition, Algeria's Khdewedj El Amia Palace had an open gallery space, or "sqifa", which divided the palace into internal and external parts, giving the interior space strong control over the entry of outside visitors [34]. In this respect, the methods used in the Forbidden City were similar, as shown in Figures 1b and 5. Qianqingmen Square, with a high integration value (1.4952), was used to separate the office space from the living space, thus reducing the accessibility of the living space. Additionally, using space syntax, an analysis of the Palace at Gede in Kenya showed that its rooms were organized in seven levels of depth [17,18], while there were 19 levels of depth in the Beijing Forbidden City and 9 levels of depth in the Shenyang Imperial Palace. Generally, the greater the level of depth of space, the stronger the enclosure of the space and the weaker the external connectivity. This indicates that the two palaces in China, especially the Beijing Forbidden City, have significantly higher spatial enclosures than the Palace at Gede.

## 5. Conclusions

This study analyzed the spatial features of the Beijing Forbidden City and the Shenyang Imperial Palace by using the relational diagram approach of the space syntax method. First, the depth value and integration value of each space were calculated by means of diagrams. Then, the results were compared and analyzed to reveal the similarities and differences among the office space, the living space, and the recreation space in these two palaces in terms of spatial enclosure and accessibility, as well as to reveal possible underlying reasons for these similarities and differences. The specific conclusions are as follows.

(1) The space settings in the Beijing Forbidden City and the Shenyang Imperial Palace were basically in line with the requirements of the spatial functions of these areas. The office space had the lowest degree of spatial enclosure, while the living space and the recreation space had relatively high degrees of enclosure. This layout was conducive to improving the convenience of using the office space and protecting the personal privacy of the emperor and his relatives.

(2) The historical status and construction background of the two palaces caused differences in the spatial features. A comparison of the same functional spaces in the two palaces showed that the office space in the Beijing Forbidden City was more enclosed than that in the Shenyang Imperial Palace, while the office space in the Shenyang Imperial Palace was more accessible than that in the Beijing Forbidden City. The spatial enclosure and accessibility of the emperor's bedchambers were significantly higher in the Forbidden City than in the Shenyang Imperial Palace, while the accessibility of the recreation space was significantly lower in the Shenyang Imperial Palace than in the Forbidden City.

(3) Factors such as construction sequence and functional conversion during the use process also affected the rationality of the spatial layout of the two palaces. The construction of the Shenyang Imperial Palace was gradually completed in three phases. The recreation space was the last to be built, and its location was somewhat unreasonable, resulting in the spatial enclosure of the recreation space being higher than (accessibility being lower than) the living space. In the process of using Beijing Forbidden City, the transfer of functional space improved the accessibility of the office space, facilitated the connection between the emperor's living space and the ministers' office space, and improved the emperor's efficiency in handling government affairs. Compared with traditional palaces in other countries, the various spaces found in the two Chinese palaces embodied a more pronounced sense of imperial power and ritual hierarchy.

The results of this paper have implications for the contemporary design of group combination buildings with different functions. First, the space syntax can be considered to calculate the degree of integration and depth values of different types of buildings in the architectural scheme stage, compare these values with building functions, and adjust the location of individual buildings accordingly. Second, in the process of functional adjustment between different buildings in the existing building group, the method of space syntax can also be used to analyze and determine whether the adjustment is reasonable. Finally, with the help of the model relationship diagram of space, it can avoid the unreasonable location of a single building due to phased construction and other reasons. In addition, by studying the spatial characteristics of these two traditional palace groups, this paper found that the scale of the building group should be accounted for in the process of building the J-graph using space syntax. If the spatial scale of the building group is large and there are many single buildings, the model relationship diagram should not be overly complicated or cumbersome. Otherwise, it might have a negative impact on the analysis of the relationship between different functional spaces.

## 6. Research Limitations

There are many limitations to this study. For example, the process of building models and calculating the integration values is based only on spatial locations. However, for heavily guarded royal palaces, levels of accessibility cannot fully reflect actual spatial use situations. Therefore, further research should be conducted on the spaces of traditional Chinese royal palaces.

**Author Contributions:** Conceptualization, D.Z. and Y.Z.; methodology, D.Z.; software, D.Z. and X.S.; validation, D.Z. and X.Z.; formal analysis, D.Z. and X.S.; data curation, X.S.; writing-original draft preparation, D.Z. and X.S.; writing-review and editing, D.Z., H.C. and Y.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Program of Humanities and Social Science Research Program of the Ministry of Education of China (22YJA760102), the Guangzhou Science and Technology Plan Project (2023A03J0080), and the Scientific Research Fund of Guangzhou University (PT252022006).

**Data Availability Statement:** The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author/s.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Yu, Z. *Palace of the Forbidden City*; People's Art Publishing House: Beijing, China, 2016. (In Chinese)
2. Bai, H.; Huang, W. The Implied Political Meaning of the Architecture of the Forbidden City. *J. Palace Mus.* **2011**, *7*, 92–100. (In Chinese)
3. Wu, B. *Palace Museum Studies and Shenyang Palace Museum*; Palace Museum Press: Beijing, China, 2017. (In Chinese)
4. Chen, B.; Wang, X. Architectural Layout under the Influence of Politics and Economy: An Analysis of the Architectural Layout of Shenyang Palace Museum East Road and Middle Road. *J. Shenyang Jianzhu Univ.* **2007**, *4*, 385–389. (In Chinese)
5. Luo, Y. Looking at the Trend of Manchu Culture from the Architecture of the Shenyang Palace Museum. *J. Shenyang Palace Mus.* **2012**, *12*, 40–49. (In Chinese)
6. Hillier, B.; Hanson, J. *The Social Logic of Space*; Cambridge University Press: Cambridge, UK, 1984.
7. Jiang, B.; Claramunt, C. Integration of Space Syntax into GIS: New Perspectives for Urban Morphology. *Trans. GIS* **2002**, *6*, 295–309. [CrossRef]
8. Jiang, B.; Claramunt, C. An integration of space syntax into GIS for modeling urban spaces. *Int. J. Appl. Earth Obs. Geoinf.* **2000**, *2*, 161–171. [CrossRef]
9. Dalton, R.; Bafna, S. The syntactical image of the city: A reciprocal definition of spatial elements and space syntaxes. In *4th International Space Syntax Symposium*; Hanson, J., Ed.; University College London: London, UK, 2003.
10. Griffiths, S.; Vaughan, L. Mapping spatial cultures: Contributions of space syntax to research in the urban history of the nineteenth-century city. *Urban Hist.* **2020**, *47*, 488–511. [CrossRef]
11. Hillier, B.; Sheng, Q. The Development Status and Future of Spatial Syntax. *J. Archit.* **2014**, *8*, 60–65. (In Chinese)
12. Yamu, C.; van Nes, A.; Garau, C. Bill Hillier's Legacy: Space Syntax—A Synopsis of Basic Concepts, Measures, and Empirical Application. *Sustainability* **2021**, *13*, 3394. [CrossRef]
13. Haq, S.; Luo, Y. Space Syntax in Healthcare Facilities Research: A Review. *HERD Health Environ. Res. Des. J.* **2012**, *5*, 98–117. [CrossRef]

14. Zhang, D.; Shi, Z.; Cheng, M. A Study on the Spatial Pattern of Traditional Villages from the Perspective of Courtyard House Distribution. *Buildings* **2023**, *13*, 1913. [CrossRef]
15. Hoeven, F.V.D.; Nes, A.V. Improving the design of urban underground space in metro stations using the space syntax methodology. *Tunn. Undergr. Space Technol.* **2014**, *40*, 64–74. [CrossRef]
16. Sheng, Q. Unraveling the Spatial Patterns of Everyday Life in Chinese Cities—A Comparative Study Between Beijing and Tianjin. *Geogr. Compass* **2014**, *8*, 601–616. [CrossRef]
17. Mahmoud, A.H.; Omar, R.H. Planting design for urban parks: Space syntax as a landscape design assessment tool. *Front. Arch. Res.* **2015**, *4*, 35–45. [CrossRef]
18. Baumanova, M. Sensory Synaesthesia: Combined Analyses Based on Space Syntax in African Urban Contexts. *Afr. Archaeol. Rev.* **2020**, *37*, 125–141. [CrossRef]
19. Nevadomsky, J.; Lawson, N.; Hazlett, K. An Ethnographic and Space Syntax Analysis of Benin Kingdom Nobility Architecture. *Afr. Archaeol. Rev.* **2014**, *31*, 59–85. [CrossRef]
20. Baumanova, M.; Šmejda, L. Structural dynamics of spatial complexity at the 'Palace of Gede', Kenya. *Azania Archaeol. Res. Afr.* **2017**, *52*, 71–99. [CrossRef]
21. Regev, E. Inside Herod's Courts: Social Relations and Royal Ideology in the Herodian Palaces. *J. Study Jud.* **2012**, *43*, 180–214. [CrossRef]
22. Zhu, J. *Chinese Spatial Strategies: Imperial Beijing 1420–1911*; Routledge: London, UK, 2004.
23. Shen, X. Inheritance and Integration: The Transformation Process of Manchu and Han Architectural Styles in the Shenyang Palace Museum. *J. Shenyang Palace Mus.* **2011**, *11*, 312–321. (In Chinese)
24. Sun, Q. Characteristics and Grades of Early Architecture in the Shenyang Palace Museum. *J. Shenyang Palace Mus.* **2009**, *8*, 88–93. (In Chinese)
25. Hillier, B. *Space Is the Machine: A Configurational Theory of Architecture*; China Building Industry Press: Beijing, China, 2007.
26. Hanson, J. *Decoding Homes and Houses*; Cambridge University Press: Cambridge, UK, 1998.
27. Moonkham, P.; Srinurak, N.; Duff, A.I. The heterarchical life and spatial analyses of the historical Buddhist temples in the Chiang Saen Basin, Northern Thailand. *J. Anthr. Archaeol.* **2023**, *70*, 101506. [CrossRef]
28. Anderson, B. *Imagined Communities: Reflections on the Origin and Spread of Nationalism*; Verso: New York, NY, USA, 2006.
29. Ashmore, W. *Construction and Cosmology: Politics and Ideology in Lowland Maya Settlement Patterns*; University of Utah Press: Salt Lake City, UT, USA, 1989.
30. Smith, A. *The Political Landscape: Constellations of Authority in Early Complex Polities*; University of California Press: Berkeley, CA, USA, 2003.
31. Monroe, J.C. *The Dynamics of State Formation: The Archaeology and Ethnohistory of Pre-Colonial Dahomey*; Department of Anthropology, University of California: Los Angeles, CA, USA, 2003.
32. Kwon, Y.; Bonghee, J.; Kim, S. The Seventeenth-century Transition of Seoul's Spatial Structure to Functional Pragmatism. *J. Asian Arch. Build. Eng.* **2015**, *14*, 419–426. [CrossRef]
33. Şalgamcıoğlu, M.E.; Edgü, E. TOPKAPI PALACE: Reflections on Social and Spatial Order. In Proceedings of the 11th International Space Syntax Symposium, SSS 2017, Lisbon, Portugal, 3–7 July 2017.
34. Benyahia, L.; Hamouda, A.; Moffok, N. Decoding the Spatial Configuration of the Ottoman Palace "Khdewedj El Amia" in Algiers (Algeria) through Space Syntax. *Prostor* **2021**, *29*, 192–211. [CrossRef] [PubMed]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

land

MDPI

*Article*

# How Should Soundscape Optimization from Perceived Soundscape Elements in Urban Forests by the Riverside Be Performed?

**Xin-Chen Hong [1,2,†], Shi Cheng [1,†], Jiang Liu [2], Lian-Huan Guo [2], Emily Dang [3], Jia-Bing Wang [2] and Yuning Cheng [1,*]**

[1] School of Architecture, Southeast University, Nanjing 210096, China; xch.hung@outlook.com (X.-C.H.)
[2] School of Architecture and Urban-Rural Planning, Fuzhou University, Fuzhou 350108, China; lianhuan.guo@outlook.com (L.-H.G.)
[3] Department of Forest Resources Management, University of British Columbia, Vancouver, BC V6T 1Z4, Canada
* Correspondence: cyn999@126.com
† These authors contributed equally to this work.

**Abstract:** Urban forests by the riverside are important habitats for various animals and contribute various soundscapes for citizens. Unfortunately, urban forests are exposed to the influence of riverside traffic noises from freeways. This study aims to explore the spatial and temporal variation of soundscape, conduct soundscape optimization for multiple parameters, and find a balance and its interval of soundscape elements through optimizing a soundscape map. Questionnaires and measuring equipment were used to gather soundscape information in an urban forested area in Fuzhou, China. Diurnal variations and soundscape mapping were used to analyze spatial and psychophysical relationships between soundscape drivers. We then conducted optimization for a soundscape map, which included normalization, critical value determination, target interval of optimal SPL determination, and modification of SPL and mapping. Our findings suggest that biological activities and natural phenomena are potential drivers for diurnal variation of soundscapes, especially tidal phenomena contributing water and shipping soundscapes. Our results also suggest that all the high values of perceived soundscapes were found at the southwest corner of the study area, which includes both riverside and urban forest elements. Furthermore, we suggest combining both optimal soundscape and SPL correction maps to aid in sustainable design in urban forests. This can contribute to the understanding and methodology of soundscape map optimization in urban forests when proposing suitable design plans and conservation of territorial sound.

**Keywords:** soundscape; urban forests; mapping; optimal process; China

**Citation:** Hong, X.-C.; Cheng, S.; Liu, J.; Guo, L.-H.; Dang, E.; Wang, J.-B.; Cheng, Y. How Should Soundscape Optimization from Perceived Soundscape Elements in Urban Forests by the Riverside Be Performed? *Land* **2023**, *12*, 1929. https://doi.org/10.3390/land12101929

Academic Editor: Eckart Lange

Received: 18 August 2023
Revised: 7 October 2023
Accepted: 10 October 2023
Published: 17 October 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

An urban forested area is an important part of urban green infrastructure. It encompasses the trees and shrubs in an urban area, including those in yards, along streets and utility corridors, in protected areas, and in watersheds [1]. Urban forests provide a variety of potential benefits to residents, such as sustainable cooling for cities [2], improved air quality [3,4], noise reduction [5], and improved sensory landscapes such as lightscapes [6], soundscapes [7,8], and smellscapes. These potential benefits play a key role in the construction of a healthy city. The World Health Organization (WHO) has announced goals for healthy cities, which aim to continuously improve the health and quality of life of city dwellers [9]. A healthy city is one that continually creates and improves its physical and social environments and expands community resources to enable people to mutually support each other. Previous studies of built environments have suggested that blue-green spaces, which are composed mainly of plants and water resources, are an important carrier

of a healthy city as they contribute to a landsense ecology in sustainable cities [10]. Urban forested areas near water also play a potential role in healthy cities as they generally have similar compositions to blue-green spaces, which suggests that we should pay more attention to these areas.

Urban forests by riversides are important habitats for various animals. These animals occupy their ecological niche in land, river, and air [11]. The location of urban forests can influence the diversity of animal species. For example, in urban downtown areas, urban forests by the riverside perform the same function as an urban waterfront park [12]. Pets are animals that often accompany their owners during recreational activities in urban downtown areas, which suggests a lack of terrestrial wildlife in urban environments [13]. Contrary to the lack of terrestrial wildlife, wild birds, especially aquatic birds by riversides, occupy the predominant positions in the forested area of downtown. In suburbs, urban forests near the riverside also function as wetlands, suggesting that various wildlife inhabits here [14]. These various animals contribute to the production of biological sound (biophony) in the soundscape. Previous studies have demonstrated that biophony can reduce pressure experienced by people living in high-density cities, further contributing to the development of healthy cities [7]. For our study, we have chosen to focus on understanding soundscapes in urban forests near the riverside.

Unfortunately, urban development has resulted in many issues for urban forests located near riversides [15,16]. As most urban rivers are located near freeways, the most notable and serious issue for urban rivers is traffic pollution, which includes air pollution from traffic emissions, light pollution from car lights, and noise pollution from car horns [17]. Some scholars have conducted research on optimal solutions for landscape visual quality assessment and urban heat mitigation [18–20]. There are differences in the penetration capacity of these pollution sources, where noise pollution is strong and easily perceived by the public. The noise pollution spreads into forested areas along freeways at urban forest boundaries, contributing to a negative effect on the soundscape [21]. Urban forest planners and landscape designers do not know how to optimize or minimize noise exposure and negative soundscapes, which is an application gap in urban scenarios. Therefore, optimizing a soundscape map is necessary for urban forests near riversides to provide optimal references for planners and designers.

Previous studies of soundscape optimization have mainly focused on optimal solutions for a single parameter, such as clarifying the optimization threshold through psychophysical laws and linear regression, auditory augmented reality, etc. [22,23]. There is a lack of optimal solutions for multiple parameters, especially when finding a balance between perceived soundscape elements. Another potential research gap is that soundscape optimization is disposable and single-round in general, which suggests that we should focus on achieving multi-round optimization for optimal soundscape. The challenges with these research gaps are how to find a balance and its interval of soundscape elements through multi-round optimization of a soundscape map and then continuously optimize the urban forest. Thus, the following three research questions were asked: (1) Do biological activities and natural phenomena influence the diurnal variation of the soundscape? (2) What is the relationship between subjective and objective data in soundscape maps? (3) How can we apply the optimal soundscape map?

We suggest multiple steps to conduct optimization for a soundscape map for multiple parameters between perceived soundscape elements and provide the possibility of multi-round optimization, contributing to being infinitely close to an extremely optimal solution after multiple rounds of optimization. SPL ($L_{Aeq}$) is the most widely used index to measure noise levels in urban and forest environments [24]. Thus, $L_{Aeq}$ is selected as a physical parameter of the optimal soundscape.

This study aims to highlight the importance of urban forests near riversides and fill some of the research gaps in optimizing a soundscape map. Specifically, this study aims to (1) explore the spatial and temporal variation of soundscape in urban forests by riverside; (2) conduct soundscape optimization for multiple parameters; and (3) find a balance and

interval of soundscape elements through soundscape map optimization. The findings and methodology developed in this study aim to contribute to soundscape conservation and sustainable design in urban forests.

## 2. Methodology

### *2.1. Study Area*

Our study was conducted in Fuzhou, Fujian, China, which has a subtropical marine monsoon climate. Our observation site was Fuzhou Beach Park (FBP), an important forested area that has a total area of 200,000 $m^2$ and widths that vary between 30 m and 200 m. FBP is located on both sides of the Hongtang Bridge, along the Wulong River (see Figure 1). FBP is also surrounded by a university and several communities; thus, FBP is mainly visited by residents, students, and tourists. The entrance to FBP is close to a freeway, which often experiences rush hour.

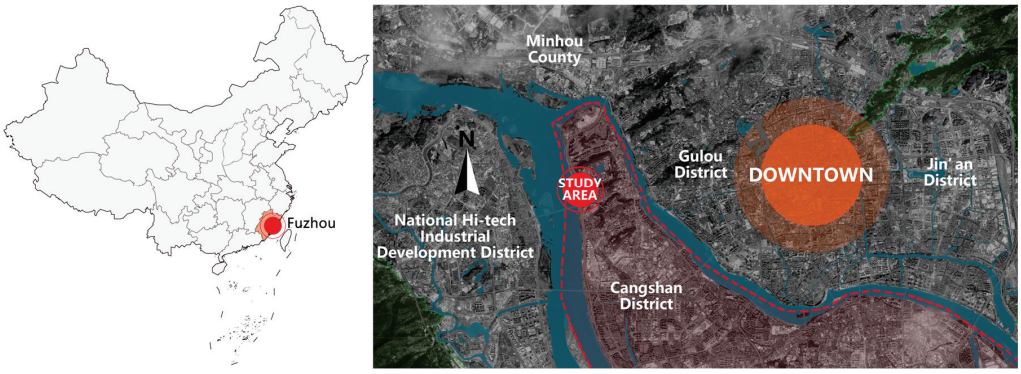



**Figure 1.** The location of the study area in Fuzhou.

To meet the demand and behavior of visitors, the area of FBP is divided into multiple functional spaces, which include urban forest space, entrance distribution space, and beach recreation space (see Figure 2). The beach recreation space is surrounded by urban forests and a river, which meets the need for visitors to be close to nature. The dominant tree species in the urban forests and entrance distribution spaces include masson pine (*Pinus massoniana*), mountain ebony (*Bauhinia purpurea*), linden (*Ficus religiosa*), and araucaria (*Araucaria cunninghamii*), whereas hemp palm (*Trachycarpusortune*) is the dominant tree species in the beach recreation space. Similarly, various animals, such as the intermediate egret (*Ardea intermedia*), myna (*Acridotheres cristatellus*), and common tern (*Sterna hirundo*), inhabit this urban forested area.

**Figure 2.** Aerial photo of Fuzhou Beach Park (**top**) and functional areas (**bottom**).

Overall, the urban forested areas within FBP contain high levels of forest cover and potential sources for sounds, which makes FBP a suitable area for soundscape research in urban forests. To contribute to soundscape mapping, seventy-eight observation sites that were evenly distributed at 30 m intervals were selected in FBP.

### *2.2. Soundscape Data*

Based on the condition of the study area, various nature resources contributed to potential soundscape resources. Questionnaires and measuring equipment were used to gather soundscape information in Fuzhou Beach Park.

A questionnaire was conducted to inquire about the perceived occurrence and pleasure of soundscapes. According to [25,26], soundscapes are comprised of three main classes: geophony, biophony, and anthrophony. Our questionnaires included: six categories for geophony, including "leaves rustling", "branches swaying" and "water", and three blank spaces; six categories for biophony, including "birdsong", "insects", "barking", and three blank spaces; and fourteen categories for anthrophony, including "traffic", "broadcast", "ringtone", "shipping", "sanitation", "plant pruning", "footsteps", "speech", "children", "singing", "peddling", and three blank spaces. The first section of the questionnaire determined the presence or absence of soundscape elements before each category. The second section utilized the following five-point ordinal scale [7,27] for the pleasantness of perceived soundscape in urban forests (PSUF) for geophony, biophony, and anthrophony: "not pleasant at all (+1)", "slightly pleasant (+2)", "moderately pleasant (+3)", "very pleasant (+4)", and "extremely pleasant (+5)". The third section asked about the questionee's information, such as age, gender, and hearing ability.

Meanwhile, we conducted a measuring process for a sound environment. SPL ($L_{Aeq}$) is the most widely spread index to measure noise levels in urban environments and forest environments [24]. Thus, this parameter was adopted to express objective information about the soundscape. The $L_{Aeq}$ was measured using Type-1 sound level meters (AWA6228+) at 1.5 m above the ground during the survey.

### *2.3. Procedure*

#### 2.3.1. Participants and Measurements

Participants were actively recruited on-site, and the majority of the participants were park visitors. A total of 317 participants (male = 149, female = 168, average 27.6 $\pm$ 3.9) with normal hearing took part in the questionnaire. Based on our participants alone, it can be said that visitors to the study area are mainly young and middle-aged. All participants were exposed to the soundscape in a standing position at each site for five minutes, and $L_{Aeq}$ was measured simultaneously using five Type-1 sound level meters. Then, the participants spent one minute filling out questionnaires. Equipment measurements were repeated three times at each observation site.

Tests were conducted on sunny days in November 2019, December 2019, and January 2020, not including holidays. The test included five time periods: morning (6:00–9:00) and (9:00–12:00), afternoon (12:00–15:00) and (15:00–18:00), and evening (18:00–21:00). The population distributions of the questionnaire in different periods were 48, 77, 54, 67, and 71 participants, respectively. Before the test began, all participants were told the details of the study and required to sign a consensus outlining the procedures and details of the survey, including content, purpose, and methodology. Furthermore, participants could quit the study at any point if they felt uncomfortable during the process.

#### 2.3.2. Optimizing a Soundscape Map

A soundscape is that acoustic environment as perceived, experienced, or understood by a person or people in context [28]. Sound sources in urban forests are generated by nature or human activity. Thus, soundscapes include the superposition and mixing of geophony, biophony, and anthrophony in urban forests [29]. We considered optimal soundscape to be

when a perceptual balance is reached among these three soundscape elements. Therefore, optimizing a soundscape map included four steps (see Figure 3).

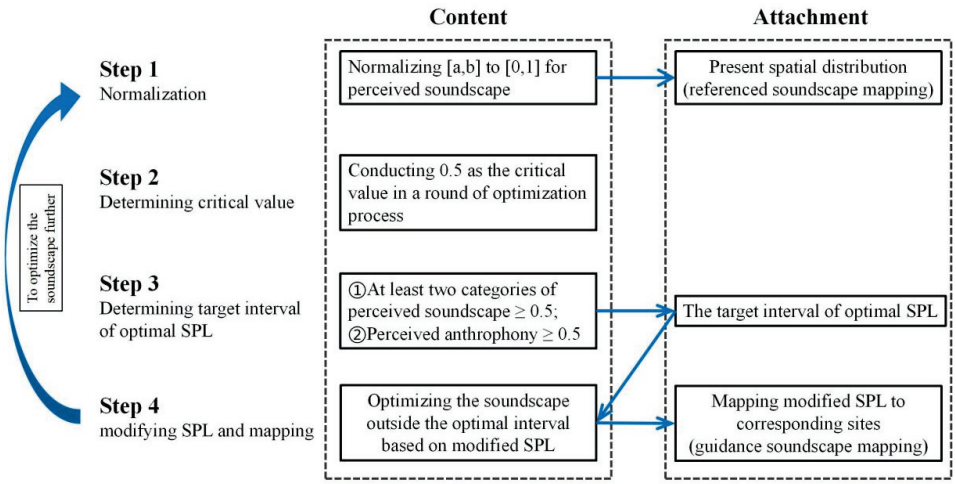



**Figure 3.** The framework of soundscape optimization.

**Step 1: Normalization.** Due to the fluctuating extremes of the perceived soundscape, we considered eliminating interval differences through normalization. The normalized interval of perceived soundscape was [0, 1] for geophony, biophony, and anthrophony. We then conducted a process of soundscape mapping as a reference to the present spatial distribution, which is performed using ArcGIS.

**Step 2: Determining the critical value.** The critical value for the perceptual balance should be considered when finding the optimal target interval of SPL ($L_{Aeq}$). After the normalization process, the 0.5 value represents the average of the perceived soundscape. To effectively and feasibly gradually improve perceived soundscape in urban forests, we considered 0.5 as the critical value of perceived soundscape in a round of optimization. Based on this critical value, multiple rounds may be performed later.

**Step 3: Determining the target interval of optimal SPL.** Based on the relationship between subjective and objective data of the soundscape, we determined the target interval of optimal SPL according to the critical value from the previous step. Previous studies have suggested that negative artificial sound weakens the positive effects of natural sound [30]. Thus, the target interval for an optimal soundscape is to find the following conditions: (1) perceived soundscape scores are 0.5 or above for at least two categories of soundscape (geophony, biophony, and anthrophony); (2) perceived anthrophony is not below 0.5.

**Step 4: Modifying SPL and mapping.** According to the obtained optimal interval, we optimized the soundscape outside the optimal interval by modifying SPL. The modified SPL data were mapped to corresponding observation sites. We then conducted a process of soundscape mapping as a guide to optimal spatial distribution.

Furthermore, by combining the referenced and guidance soundscape mapping, we could propose suitable design plans for different spatial locations. If we wanted to optimize the soundscape further, we would start from the first step again and conduct multiple optimal processes.

## 3. Result

### *3.1. Diurnal Variation of Soundscape*

#### 3.1.1. Perceived Soundscape Elements at Different Time Periods

Perceived soundscape elements obtained from questionnaires were summed and classified. This included "leaves rustling", "branches swaying", and "water" for geophony; "birdsong", "footsteps", "speech", "insects", "peddling", "barking", "children", and "singing" for biophony; and "traffic", "broadcast", "ringtone", "shipping", "sanitation", and "plant pruning" for anthrophony. These perceived soundscape elements suggest that there are

various soundscapes in the study area. As shown in Figure 4, our results indicated that anthrophony occupies a majority of the soundscape (accounting for 58.82%), and the periodicity of the anthrophony also influences soundscape variation. Thus, a diurnal variation analysis of the perceived soundscape (see Figure 5) was conducted.

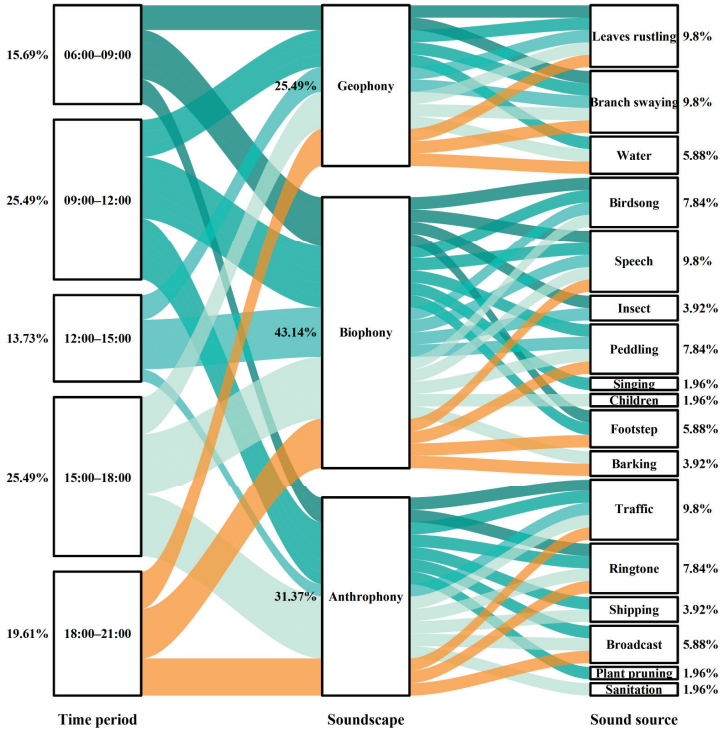



**Figure 4.** Composition of the soundscape at different time periods.

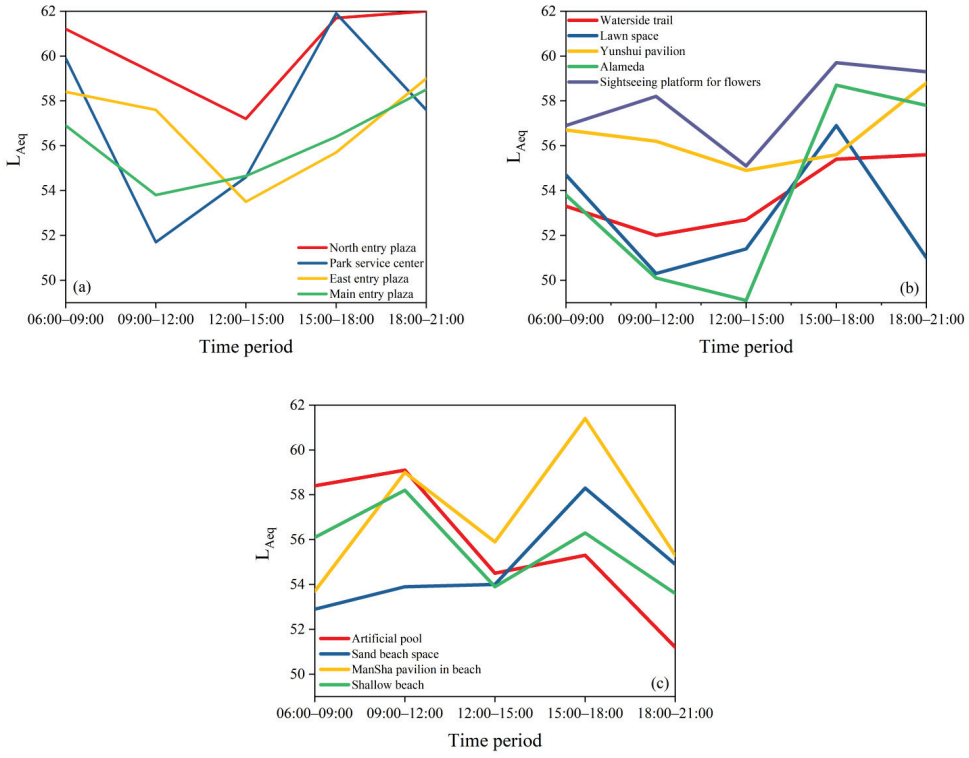



**Figure 5.** The SPL of entrance distribution space (**a**), urban forest space (**b**), and beach recreation space (**c**) at different time periods.

The above figure demonstrates that "leaves rustling", "branches swaying" in geophony, and "speech" in anthrophony were distributed in all time periods, which suggests that the natural phenomena of river wind and individuals' speech may occur in diurnal variation. Between the period of 9:00–12:00, there was a maximal gap of perceived soundscape elements between natural sound (geophony and biophony) and unnatural sound (anthrophony), with a ratio of 4:9. There was a minimal difference in perceived soundscape elements between the period of 6:00–9:00, with a ratio of 1:1. but the number of biophony and anthrophony elements remained the same during this time. Specifically, results showed that "birdsong" and "peddling" occurred before night (18:00–21:00) and after morning (06:00–09:00), respectively. These sound elements were also dominant throughout the day, with an overlapping period between 09:00 and 18:00. This suggested that the most frequent biological and human activities in the study area occur between 09:00–18:00. We also found that when "shipping" was perceived, "water" would also be perceived, which indicated a potential relationship between the sailing time and tide.

#### 3.1.2. Sound Pressure Level in Main Distribution Spaces

The flow rate of individuals influences the sound pressure level of the main distribution spaces. Figure 5 shows the SPL of each distribution space within the main distribution spaces, which include the entrance distribution space, urban forest space, and beach recreation space. The period with the lowest SPL was between 12:00 and 15:00 and occurred mainly in the urban forest area, which indicated low biological activities at this time. The period with the highest SPL was between 18:00 and 21:00 and was found to occur mainly in the entrance distribution space. Similarly, our results also showed that periods of high SPL were found at 06:00–09:00 and 15:00–18:00, which suggested a potential relation between biological activities and rush hour. Interestingly, we found that the average SPL of urban forest space was higher than that of beach recreation areas between 18:00 and 21:00, and bird activity decreased after dusk, which suggested that individuals may participate in more recreational activities at night in nearby green spaces than water.

Our results showed that the "North entry plaza" had the most periods where the SPL was at its highest, which was distributed in the interval [57.2, 62.0] dBA. We also found that SPL at the "North entry plaza" decreased during the non-rush hour between 9:00 and 15:00. This may be due to the entry plaza being near an expressway, where SPL may have been influenced by traffic noise. In the urban forest space, the SPL for "Sightseeing platform for flowers" was highest and distributed in the interval [56.9, 59.7] dBA. The "Sightseeing platform for flowers" acts as a transition space between the urban forest and beach recreation spaces and plays a role in the function of stopping and staying for rest. In the beach recreation space, the SPL for "Mansha pavilion in beach" was highest and most distrusted in the interval [53.7, 61.4] dBA. This space acts not only as a resting place, but also as an active place for beach activities.

### *3.2. Soundscape Mapping*

The psychological quantity of geophony, biophony, and anthrophony was distributed in the intervals [2.6, 3.9], [2.3, 3.6], and [1.1, 2.3], respectively. We then conducted a normalization process to transfer the interval to [0, 1]. The process of soundscape mapping was then conducted based on the subjective and objective data of the soundscape (see Figure 6).

Figure 6a shows that high SPL was distributed in the "North entry plaza" and the nearby urban forest space, followed by the "Main entry plaza", while the beach recreation space presented a relatively low SPL. Figure 6b demonstrates that the positive perception of geophony was mainly distributed to the beach recreation space and urban forest space, which suggested an attention tendency for individuals to water and plant space. As shown in Figure 6c, the positive perception of biophony was mainly distributed to the urban forest space and entrance distribution space, which may be attributed to an attraction towards birds in plants nearby the entrance distribution space and existing plants in the urban forest

space. Furthermore, our results showed that the negative perception of anthrophony was mainly distributed to urban forest space, but this distribution trend was opposite for beach recreation space and entrance distribution space (see Figure 6d).

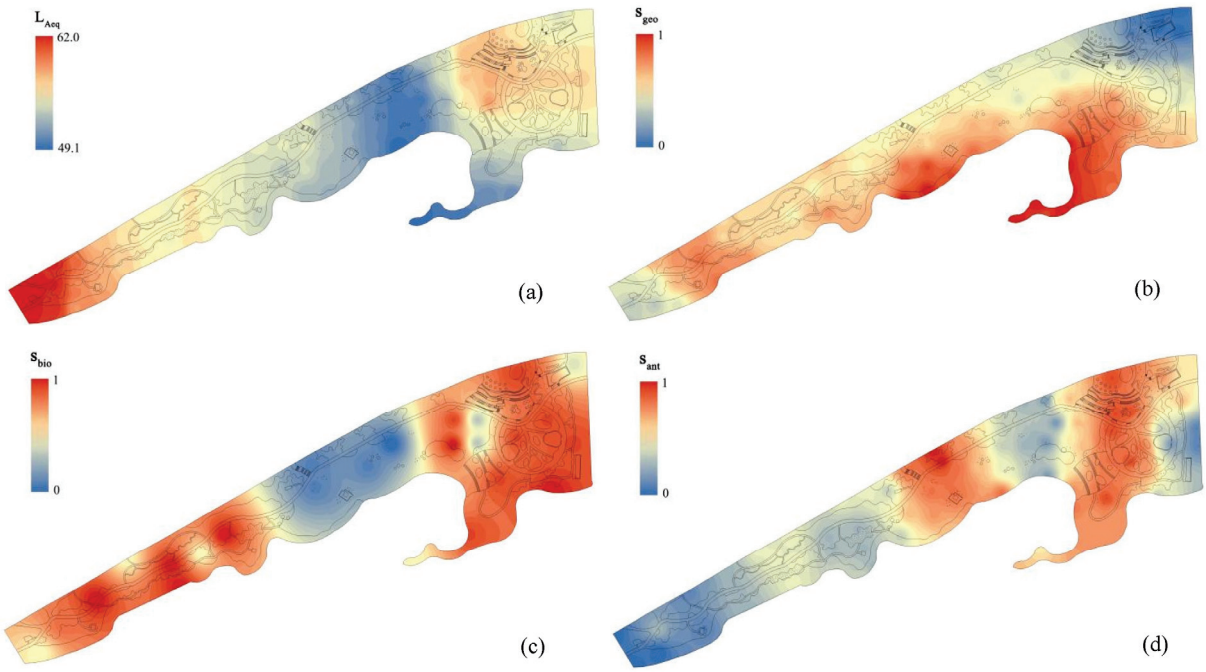



**Figure 6.** The soundscape maps of SPL (**a**), geophony (**b**), biophony (**c**), and anthrophony (**d**).

When the results from Figure 5a,b are combined, we can see that, from the low SPL and the positive perception of geophony around the waterfront, the SPL of water soundscapes is relatively low. These combined figures also show that high SPL and the positive perception of geophony are mainly distributed in urban forest space, which suggests that wind energy causes leaves and branches to vibrate and produce strong sound energy. Likewise, when Figure 6a,c are combined, our results show a similar tendency between SPL and perceived biophony, suggesting a balance between the sound environment and biological activities. Additionally, as shown both in Figure 6a,d, there is a negative relationship between SPL and perceived anthrophony in beach recreation spaces, especially around the waterfront, and an opposite tendency in the "Main entry plaza".

### *3.3. Optimal Soundscape Interval and Guided Mapping*

Through quadratic fitting analysis, our results showed a positive relationship between SPL and natural soundscape (geophony and biophony), with R-squared being 0.93 and 0.90, respectively. Likewise, there was a negative relationship between SPL and unnatural soundscape (anthrophony), with R-squared being 0.93. Specifically, most scores of perceived biophony were higher than perceived geophony when SPL was the same.

Furthermore, Figure 7 (left) demonstrates that the target SPL interval of the optimal soundscape was [51.6, 56.2]. When SPL was higher than 51.6 dBA within this interval, the scores of perceived geophony and anthrophony both exceeded 0.5. Similarly, when SPL was higher than 53.2 dBA, perceived biophony exceeded 0.5. Figure 7 (left) also shows that when the SPL exceeded 56.2 dBA, the score of perceived anthrophony would be lower than 0.5, suggesting that this SPL is a critical value in the optimal interval.

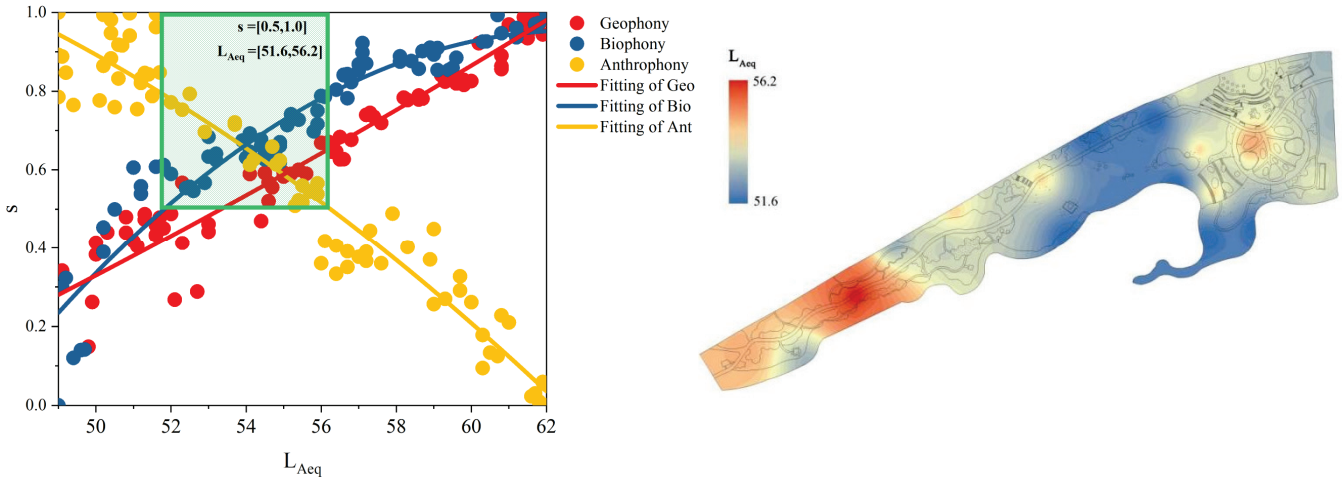



**Figure 7.** Optimal soundscape interval (**left**) and guided soundscape map (**right**).

Following the goal of obtaining an optimal interval, we maintained, enhanced, and weakened the soundscape by modifying SPL at our observation sites. The modified process included maintaining SPL within the optimal interval, enhancing SPL if the value was lower than 51.6 dBA to the optimal interval, and weakening SPL if the value was higher than 56.2 dBA to the optimal interval. We then conducted soundscape mapping for SPL after the modification process. Figure 7 (right) shows that high SPL was distributed in the "Park service center" and urban forest space, while low SPL was distributed in the beach recreation space.

## 4. Discussion

### *4.1. Biological Activities and Natural Phenomena Influencing Diurnal Variation of the Soundscape*

Humans tend to engage in recreational activities in natural environments, especially in areas that contain water and plants [31]. These two conditions are simultaneously met in urban forests located by the riverside. Forests are habitats for many creatures, especially birds, which suggests that the biological and human activity cycle may influence the diurnal variation of the soundscape [32].

Our findings showed that various biological and human activities are performed at different time periods (see Figures 4 and 5). Between the period of 6:00 and 9:00, we observed high SPL contributed by the following: a peak in birdsong activity, rush hour traffic, and morning exercises performed by the locals (e.g., Tai Chi, ball games, and running). We found that SPL decreased after 9:00 as several shops in the study area opened, the number of morning exercisers decreased, and rush hour ended. Between noon and late afternoon (12:00–15:00), we observed a gradual decrease in biophony. Then, there was a second birdsong peak at dusk and an increasing number of visitors during this period. Between 18:00 and 21:00, various commercial and human activities (e.g., walks along the river beach, exercises, family activities, etc.) occurred that contributed to a high SPL.

Traffic roads are generally built along rivers in urban areas [33]. This is consistent with our study area, and traffic noises outside our area were perceived at all times during our study. In addition to the traffic noise, the sounds of broadcasts and ringtones, common characteristics of urban parks, often occupy dominant positions in anthrophony [34].

Natural phenomena can influence the diurnal variation of the soundscape. As a ventilation corridor, the Wulong River channel generates periodic winds to urban forests located nearby the riverside, which promotes the soundscape occurrence of leaves rustling and branches swaying [35]. Similarly, the water soundscape can be influenced by tidal phenomena caused by the river. During our survey, the tidal phenomena of the Wulong River included four tide processes: (1) the first low tide occurred from 0:00 to 6:10; (2) the first high tide occurred from 6:11 to 11:20; (3) the second low tide occurred from 11:21 to

18:40; and (4) the second high tide occurred from 18:41 to 23:30. The high and low tides contributed to water soundscapes, which might be difficult to perceive if tidewaters were over a long distance from the riverside. As tide direction is beneficial to conserving the navigational energy of ships, the ships docked at the harbor followed the high tide in and the low tide out [36].

### *4.2. Relationship of Soundscape Maps between Subjective and Objective Data*

Figure 6 shows the complexity mechanism of soundscape maps in urban forests located nearby the riverside, which is different from that of soundscape maps for non-waterfront urban open space [37]. This complexity mechanism was reflected in the tendency toward continuous distribution for perceived geophony. The tendency toward discontinuous distribution for perceived biophony indicates that the effects of land heterogeneity play a role in plant density and biological activities [38]. Our findings suggested that the perception value of anthrophony in urban forests near riversides is higher than that of non-waterfront urban open space, which indicated the optimization effect of water soundscape [39]. Interestingly, there was a high value of perception for all soundscape elements (geophony, biophony, and anthrophony) at the southwest corner of the study area. This area was not only the furthest away from the entrance distribution space with the lowest SPL, but also included both riverside and urban forest elements. Thus, we suggest that it is necessary and important to plan a quiet space with riverside and urban forest elements (see Figure 7, right) through further noise reduction design.

With the exception of biological activities, natural phenomena, and external traffic noise, the number of paths and trails was also a potential driver for soundscape in urban forests by the riverside. There was only one path in the beach recreation space, indicating that open spaces may contribute to sound diffusion at trail paths [40]. The beach recreation space was also less affected by sounds reflected from tree leaves on the ground, as the sand in this area seemed to absorb the sound. Furthermore, birds do not tend to settle on palm trees in beach recreation spaces, calling for consideration of plants that attract birds. The open areas with a presence of non-paths (beach and platform) are the locations where people mainly partake in recreational and commercial activities. Our findings showed that the potential tolerance for anthrophony, which was generated during recreational activities, contributed to a higher value of perceived anthrophony, which suggested a consideration for maintaining the present soundscape.

### *4.3. Application of the Optimal Soundscape Map*

Optimal soundscape intervals and guided mapping contributed to the optimization of the study area. By observing normalized relationships, our findings showed that the psychological value intervals of geophony, biophony, and anthrophony are optimized from [2.6, 3.9], [2.3, 3.6], and [1.1, 2.3], to [3.3, 3.9], [3.0, 3.6], and [1.7, 2.3], respectively. This suggested that the positive perception of geophony and biophony in urban forests near riversides changed after optimization [41]. As there were traffic roads built nearby the study area, there was a limited ability to optimize anthrophony throughout the site, suggesting that we may need to appropriately increase plant density on the outer boundaries of urban forests close to traffic roads to better optimize anthrophony.

We conducted the superposition and subtraction of the two figures when Figures 6a and 7 (right) were combined. Figure 8 shows the result of the SPL correction contributing to optimal practice guidance. This figure suggests that sound environment optimization is unnecessary when in urban forest space, which indicates a consideration for conservation and maintenance. We also suggested that landscape designers optimize the SPL of the north entry plaza and beach recreation space, which indicates considerations for noise reduction and various soundscapes, respectively. Thus, we suggest that contributing government managers and landscape designers should use both the optimal soundscape map and the SPL correction map when proposing suitable design plans. If the optimal goal of the design

plans were achieved, we could conduct the application of optimal soundscape maps again, suggesting further optimizing the soundscape in urban forests.

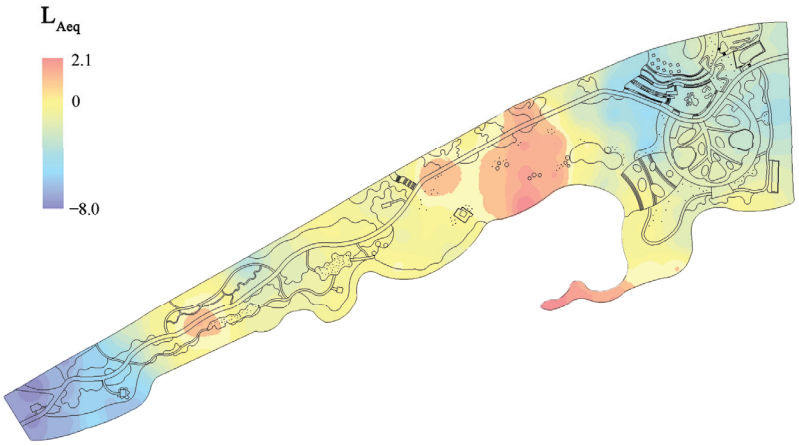



**Figure 8.** SPL Correction of soundscape map.

Some limitations may exist in our study. Although we tried to transform optimal soundscape perception into a soundscape map for guidance in urban forests near riversides, the details of external traffic were not considered a key driver of soundscape inside urban forests. Considering the difference in dominant tree species, results may show the soundscape in subtropical cities, but the framework of soundscape optimization is adapted to places where geophony, biophony, and anthrophony are present. Furthermore, diurnal variation of visual and lightscape may potentially influence auditory attention, which suggests a diurnal variation in the sensitivity variation of perceived soundscape.

## 5. Conclusions

Urban forests located near the sides of rivers are often exposed to the influence of riverside traffic noise from freeways. We found that in terms of diurnal variation of soundscape, biological activities and natural phenomena were potential drivers, especially those from tidal phenomena that contribute to water and shipping soundscape. Soundscape optimization was conducted in Fuzhou Beach Park in Fuzhou, China, which included soundscape normalization, critical value determination, target interval of optimal SPL determination, SPL modification, and mapping. We suggest combining both optimal soundscape and SPL correction maps for sustainable design in urban forests. Cooperative optimization of audio-visual interaction may need to be considered in future studies to further conduct an optimal perception process for multi-sensory experiences.

**Author Contributions:** Conceptualization, X.-C.H. and S.C.; methodology, X.-C.H.; validation, S.C., J.L. and L.-H.G.; investigation, X.-C.H. and S.C.; resources, J.L.; data curation, J.-B.W.; writing—original draft preparation, X.-C.H.; writing—review and editing, E.D.; supervision, Y.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This project was supported by the National Natural Science Foundation of China (52208052, 51838003), the National Key Research and Development Program of China (2019YFD1100405), and the Program of Humanities and Social Science Research Program of the Ministry of Education of China (Grant No. 21YJCZH038).

**Data Availability Statement:** The original research data has been presented in the figures of article.

**Acknowledgments:** The authors appreciate the valuable comments of editors and anonymous reviewers. Hao Zhang is acknowledged for useful discussions.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. Escobedo, F.J.; Kroeger, T.; Wagner, J.E. Urban forests and pollution mitigation: Analyzing ecosystem services and disservices. *Environ. Pollut.* **2011**, *159*, 2078–2087. [CrossRef] [PubMed]
2. Santamouris, M. Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* **2014**, *103*, 682–703. [CrossRef]
3. Guo, H.; Li, W.; Yao, F.; Wu, J.; Zhou, X.; Yue, Y.; Yeh, A.G. Who are more exposed to PM 2.5 pollution: A mobile phone data approach. *Environ. Int.* **2020**, *143*, 105821. [CrossRef] [PubMed]
4. Qi, J.; Lan, D.; Samsung, L. Planning for cooler cities: A framework to support the selection of urban heat mitigation techniques. *J. Clean. Prod.* **2020**, *275*, 122903. [CrossRef]
5. Yang, F.; Yi, B.Z.; Zhu, Z.J. An assessment of psychological noise reduction by landscape plants. *Int. J. Environ. Res. Public Health* **2011**, *8*, 1032–1048. [CrossRef] [PubMed]
6. Hong, X.-C.; Wang, G.Y.; Liu, J.; Dang, E. Perceived loudness sensitivity influenced by brightness in urban forests: A comparison when eyes were opened and closed. *Forests* **2020**, *11*, 1242. [CrossRef]
7. Hong, X.-C.; Wang, G.; Liu, J.; Song, L.; Wu, E. Modeling the impact of soundscape drivers on perceived birdsongs in urban forests. *J. Clean. Prod.* **2021**, *292*, 125315. [CrossRef]
8. Ma, K.W.; Mak, C.M.; Hai, M.W. Effects of environmental sound quality on soundscape preference in a public urban space. *Appl. Acoust.* **2021**, *171*, 107570. [CrossRef]
9. Boulos, M.K.; Al-Shorbaji, N.M. On the internet of things, smart cities and the who healthy cities. *Int. J. Health Geogr.* **2014**, *13*, 10. [CrossRef]
10. Han, L.; Shi, L.; Yang, F.; Xiang, X.Q.; Gao, L. Method for the evaluation of residents' perceptions of their community based on landsenses ecology. *J. Clean. Prod.* **2020**, *281*, 124048.
11. Magroski, L.M.; Pessoa, A.; Lucena, W.; Loures-Ribeiro, A.; Araújo, C.B.D. Where to release birds seized from illegal traffic? the value of vocal analyses and ecological niche modeling. *Perspect. Ecol. Conserv.* **2017**, *15*, 91–101. [CrossRef]
12. Fei, F.; Wang, Y.; Jia, X. Assessment of the mechanisms of summer thermal environment of waterfront space in China's cold regions. *Sustainability* **2022**, *14*, 2512. [CrossRef]
13. Duquette, C.A.; Loss, S.R.; Hovick, T.J. A meta-analysis of the influence of anthropogenic noise on terrestrial wildlife communication strategies. *J. Appl. Ecol.* **2021**, *58*, 1112–1121. [CrossRef]
14. Silva-Rodríguez, E.A.; Gálvez, N.; Swan, G.J.F.; Cusack, J.J.; Moreira-Arce, D. Urban wildlife in times of covid-19: What can we infer from carnivore sightings in urban areas? *Sci. Total Environ.* **2020**, *765*, 142713. [CrossRef] [PubMed]
15. Nicholas, A.P.; Quine, T.A. Crossing the divide: Representation of channels and processes in reduced-complexity river models at reach and landscape scales. *Geomorphology* **2007**, *90*, 318–339. [CrossRef]
16. Wang, M.; Zhang, D.Q.; Su, J.; Dong, J.W.; Tan, S.K. Assessing hydrological effects and performance of low impact development practices based on future scenarios modeling. *J. Clean. Prod.* **2018**, *179*, 12–23. [CrossRef]
17. Sarnat, J.A.; Golan, R.; Greenwald, R.; Raysoni, A.U.; Kewada, P.; Winquist, A.; Sarnat, S.E.; Flanders, W.D.; Mirabelli, M.C.; Zora, J.E.; et al. Exposure to traffic pollution, acute inflammation and autonomic response in a panel of car commuters. *Environ. Res.* **2014**, *133*, 66–76. [CrossRef]
18. Qi, J.; Lin, E.S.; Tan, P.Y.; Ho, R.C.; Sia, A.; Olszewska-Guizzo, A.; Zhang, X.; Waykool, R. Development and application of 3D spatial metrics using point clouds for landscape visual quality assessment. *Landsc. Urban Plan.* **2022**, *228*, 104585. [CrossRef]
19. Wang, M.; Liu, M.; Zhang, D.; Qi, J.; Fu, W.; Zhang, Y.; Rao, Q.; Bakhshipour, A.E.; Tan, S.K. Assessing and optimizing the hydrological performance of Grey-Green infrastructure systems in response to climate change and non-stationary time series. *Water Res.* **2023**, *232*, 119720. [CrossRef]
20. Qi, J.; Lan, D.; Samsung, L. Application of a decision-making framework for multi-objective optimisation of urban heat mitigation strategies. *Urban Clim.* **2023**, *47*, 101372. [CrossRef]
21. Grunst, M.L.; Grunst, A.S.; Pinxten, R.; Eens, M. Little parental response to anthropogenic noise in an urban songbird, but evidence for individual differences in sensitivity. *Sci. Total Environ.* **2021**, *769*, 144554. [CrossRef] [PubMed]
22. Chi, C.F.; Dewi, R.S.; Huang, M.H. Psychophysical evaluation of auditory signals in passenger vehicles. *Appl. Ergon.* **2017**, *59*, 153–164. [CrossRef] [PubMed]
23. Hong, J.Y.; Lam, B.; Ong, Z.T.; Ooi, K.; Tan, S.T. A mixed-reality approach to soundscape assessment of outdoor urban environments augmented with natural sounds. *Build. Environ.* **2021**, *194*, 107688. [CrossRef]
24. Kang, J. From dBA to soundscape indices: Managing our sound environment. *Front. Eng. Manag.* **2017**, *4*, 184–192. [CrossRef]
25. Krause, B. Anatomy of the soundscape: Evolving perspectives. *J. Audio Eng. Soc. Audio Eng. Soc.* **2008**, *56*, 73–80.
26. Pijanowski, B.C.; Farina, A.; Gage, S.H.; Dumyahn, S.L.; Krause, B.L. What is soundscape ecology? An introduction and overview of an emerging new science. *Landsc. Ecol.* **2011**, *26*, 1213–1232. [CrossRef]
27. *ISO/TS 12913-2:2018*; Acoustics—Soundscape—Part 2: Data Collection and Reporting Requirements. ISO (International Organization for Standardization): Geneva, Switzerland, 2018.
28. *ISO/TS 12913-1:2014*; Acoustics—Soundscape—Part 1: Definition and Conceptual Framework. ISO (International Organization for Standardization): Geneva, Switzerland, 2014.
29. Manzano, J.V.; Almagro, J.; Quesada, R.G. The importance of changing urban scenery in the assessment of citizens' soundscape perception. on the need for different time-related points of view. *Noise Mapp.* **2021**, *8*, 138–161. [CrossRef]

30. Kogan, P.; Arenas, J.P.; Bermejo, F.; Hinalaf, M.; Turra, B. A green soundscape index (GSI): The potential of assessing the perceived balance between natural sound and traffic noise. *Sci. Total Environ.* **2018**, *642*, 463–472. [CrossRef]
31. Jiang, B.; Xu, W.; Ji, W.; Kim, G.; Pryor, M.; Sullivan, W.C. Impacts of nature and builtacoustic-visual environments on human's multidimensional mood states: Across-continent experiment. *J. Environ. Psychol.* **2021**, *77*, 101659. [CrossRef]
32. Hong, X.-C.; Liu, J.; Wang, G.Y.; Jiang, Y.; Wu, S.T.; Lan, S.R. Factors influencing the harmonious degree of soundscapes in urban forests: A comparison of broad-leaved and coniferous forests. *Urban For. Urban Green.* **2019**, *39*, 18–25. [CrossRef]
33. Clair, C. Comparative permeability of roads, rivers, and meadows to songbirds in banff national park. *Conserv. Biol.* **2010**, *17*, 1151–1160. [CrossRef]
34. Jeon, J.Y.; Lee, P.J.; You, J.; Kang, J. Acoustical characteristics of water sounds for soundscape enhancement in urban open spaces. *J. Acoust. Soc. Am.* **2012**, *131*, 2101. [CrossRef] [PubMed]
35. Hong, X.-C.; Zhu, Z.P.; Liu, J.; Geng, D.H.; Lan, S.R. Perceived occurrences of soundscape influencing pleasantness in urban forests: A comparison of broad-leaved and coniferous forests. *Sustainability* **2019**, *11*, 4789. [CrossRef]
36. Pei, Y.L.; Chen, D.J. Study on the optimal dispatching algorithm of ships in and out of tidal two-way channel. In Proceedings of the IEEE 4th Information Technology and Mechatronics Engineering Conference (ITOEC), Chongqing, China, 14–16 December 2018; pp. 324–329.
37. Lavandier, C.; Aumond, P.; Gomez, S.; Dominguès, C. Urban soundscape maps modelled with geo-referenced data. *Noise Mapp.* **2016**, *3*, 278–294. [CrossRef]
38. Linke, J.; Franklin, S.E.; Hall-Beyer, M.; Stenhouse, G.B. Effects of cutline density and land-cover heterogeneity on landscape metrics in western alberta. *Can. J. Remote Sens.* **2008**, *34*, 390–404. [CrossRef]
39. Hong, J.Y.; Jeon, J.Y. Relationship between spatiotemporal variability of soundscape and urban morphology in a multifunctional urban area: A case study in seoul, korea. *Build. Environ.* **2017**, *126*, 386–395. [CrossRef]
40. Guillaume, G.; Picaut, J.; Dutilleux, G. Use of the transmission line matrix method for the sound propagation modelling in open-space. *J. Acoust. Soc. Am.* **2021**, *123*, 3924. [CrossRef]
41. Hong, X.-C.; Liu, J.; Wang, G.-Y. Soundscape in Urban Forests. *Forests* **2022**, *13*, 2056. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

land

MDPI

*Article*

# Natural Dose of Blue Restoration: A Field Experiment on Mental Restoration of Urban Blue Spaces

**Shixian Luo [1], Jing Xie [2,*], Huixin Wang [2], Qian Wang [2], Jie Chen [2], Zhenglun Yang [2] and Katsunori Furuya [2]**

[1] School of Architecture, Southwest Jiaotong University, Chengdu 611756, China; shixianluo@yahoo.com
[2] Graduate School of Horticulture, Chiba University, Chiba 271-8510, Japan; cefa5056@chiba-u.jp (H.W.); 20hd0402@student.gs.chiba-u.jp (Q.W.); cdga0939@chiba-u.jp (J.C.); yangzl29@yahoo.com (Z.Y.); k.furuya@faculty.chiba-u.jp (K.F.)
* Correspondence: 21hd5402@student.gs.chiba-u.jp

**Abstract:** Urban Blue Spaces (UBS) have been found to be beneficial to people's mental health. Yet, the empirical evidence for how and why different types of urban blue spaces could promote residents' mental health is still limited. Accordingly, 164 observation samples were collected for this experiment relating to the restorative perception of environmental exposure. The effects of two exposure behaviors (15 min of viewing and 15 min of walking) on psychological recovery in three different urban blue spaces settings (Urban River, Urban Canal, Urban Lake) were investigated in a field experiment. These are the main findings of this current study: (1) all three UBSs increased vitality, feelings of restoration, and positive emotions, and decreased negative emotions; (2) the mental restoration effects between walking and viewing among the three UBSs showed no significant differences; (3) of the three UBSs, urban rivers and urban lakes were the most restorative, while urban canals were less so; (4) the concept of "natural health dose" is proposed, where the health experiences of different UBSs in urban settings can show differences depending on the natural components and their levels of the environment (blue, blue + green, blue + blue). The results of this experiment can provide fundamental evidence that can contribute to building healthy cities through the management and design of different blue spaces.

**Keywords:** urban blue space; natural health dose; perceived blue level; perceived green level; environment and mental health

**Citation:** Luo, S.; Xie, J.; Wang, H.; Wang, Q.; Chen, J.; Yang, Z.; Furuya, K. Natural Dose of Blue Restoration: A Field Experiment on Mental Restoration of Urban Blue Spaces. *Land* **2023**, *12*, 1834. https://doi.org/10.3390/land12101834

Academic Editors: Xin-Chen Hong, Baojie He, Jiang Liu, Jinda Qi, Guangyu Wang and Shi Cheng

Received: 19 June 2023
Revised: 5 July 2023
Accepted: 7 July 2023
Published: 26 September 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

### *1.1. Urban Health Problems and Blue-Green Solutions*

Rapid urbanization and unhealthy lifestyles are threatening human health and quality of life [1]. According to reports, there is a link between the built environment and health problems. For example, densely developed artificial urban environments reduce the health of residents [2]; urban residents are at a significantly increased risk of anxiety and mood disorders [3]; more urban living environments are associated with higher rates of prescriptions for psychotropic medications for anxiety, depression, and psychosis [4]; spending time in urban environments significantly reduces positive emotions and increases stress and fatigue [1]. Accordingly, there is growing recognition that the urban environment is critical to public health and well-being. Mitigating the negative effects of the modern urban environment and controlling stress-related mental health problems are topics of increasing interest to urban planners and managers [5]. It has been proposed to provide and maintain health-promoting natural elements/resources in the urban environment, such as blue spaces (rivers, creeks, ponds) [6] and green spaces (urban forests, parks, green roofs) [7]. These blue–green spaces, as natural extensions of the city, can improve the urban living environment and positively influence the health level of citizens [7].

### *1.2. Lack of Empirical Studies on the Restorative Effects of Urban Blue Space*

Evidence for the importance of blue spaces for human health is also increasing but remains limited compared to green space studies [8]. Blue space is defined as "health-enabling places and spaces, where water is at the center of a range of environments with identifiable potential for the promotion of human wellbeing" [9]. Additionally, Urban Blue Space (UBS) is often considered an important component of urban development because it contributes to sustainability, landscape setting, environmental quality, quality of life, and human health [10]. These urban blue elements can be permanent or non-permanent, natural or artificial [10]. Many studies have begun to highlight the various benefits of blue spaces, such as higher life satisfaction [11], better self-reported general and mental health [12], higher physical activity [13], self-reported recreational visits [14], and increased aesthetic experiences and positive emotions [10]. However, most of the current research on blue space focuses on city/regional level population survey data (e.g., a deprived neighborhood of Plymouth in the United Kingdom [15], England [11], the city of Plovdiv, Bulgaria [12], 18 countries and regions around the globe [13], 40 small towns in central and northeast Pennsylvania [14]), and theoretical studies in laboratory settings (e.g., 10 urban park blue space images [16], 120 photographs of natural and built scenes [17], the six types of waterscapes [18], the four models as surrogates for real ponds [19], 70 color slides of natural environments containing water [20]). There is still a lack of field-based empirical studies on the health outcomes of blue spaces in urban environments. Hermanski et al. (2022) showed that although both viewing and visiting blue spaces can improve mental health, visiting blue spaces has greater benefits for mental health [21]. Therefore, field-based experimental evidence is necessary because it can increase our understanding of how blue spaces in real urban environments provide health benefits. Although previous studies at the city/regional level have a solid evidence base [22–24], empirical studies provide a more direct understanding of how blue space affects mental recovery and are more realistic and reliable relative to laboratory settings [25]. Furthermore, the findings could provide urban planners/managers with important knowledge and insights into natural interventions that promote the health of urban residents.

### *1.3. Restorative Effects May Differ between UBSs*

UBS often includes different types of blue spatial structures that are distributed in cities [8], forming a blue health network in urban environments in the form of points (fountain, pool), lines (creek, river, canal) and planes (lake, pond, lagoon). However, not all UBSs are thought to provide health benefits, as some waterways appear to result in negative health experiences, such as decreased feelings of safety and reduced positive emotions [26,27]. Furthermore, the restorative properties of different characterized natural environments have been discussed [28–31], and these findings suggest that even though the studied environments are all considered restorative, the positive effects of different environmental settings may be different for its different environmental content. Although the study by McDougall et al. (2022) has demonstrated that blue space types can vary in their ability to promote health, the results are still based on national-level online surveys [32]. Therefore, more empirical studies are needed to clarify the health benefits (or the existence of such benefits, if any) of different UBSs.

### *1.4. The Current Research Objectives*

In previous studies, psychological recovery from the environment has focused on its positive effects on psychological indicators, such as stress relief, increased attention, reduced anxiety, improved emotional state, and increased subjective vitality [5,30,31,33,34]. Similarly, this study aimed to measure the restorative benefits of UBS through the improvements in physiological indicators in participating subjects after the field experiment. The restorative outcomes of these indicators are usually measured using questionnaires [31].

In summary, the main objective of this study was to investigate the psychological recovery effects of different UBSs in an urban environment. Similar to other studies [1,5],

built-up areas without water bodies were used as a control group for the experiment. Furthermore, previous studies have shown that different behavioral and experimental phases lead to different recovery effects [30,31,35]. Therefore, specifically, the aim was to investigate the effects of the two behaviors "viewing" and "walking" on psychological indicators (subjective vitality, emotions, and perceived restoration) in different UBSs, and to discuss the reasons for the differences (if any exist) in the restorative effects of different types of UBS.

## 2. Methodology

### *2.1. Study Sites*

Blue spaces with different characteristics in the urban environment were selected for field experiments in this study. Additionally, owing to the study setting, we primarily selected freshwater blue spaces (i.e., coastal blue spaces such as harbors and waterfronts were not included). Although the spatial coverage of freshwater is much smaller than that of marine environments, investigating freshwater blue spaces is of great value in promoting broader urban health, as more than 50% of the global population lives within 3 km of freshwater [6]. Furthermore, Poulsen et al. (2022) highlighted how the health effects of non-coastal freshwater blue spaces remain underexplored [15]. Moreover, little is known about the potential of different freshwater blue space types, such as lakes, rivers, and canals, to contribute to health and well-being [32]. Therefore, three freshwater UBSs commonly found in urban environments (urban river, urban canal, urban lake) were selected as sites for investigation.

To avoid residual effects, participants visited one of four different environmental settings located in a Japanese city on different days. These four study locations were: (1) Sakagawa; (2) Shinsakagawa; (3) Osagamicyousetuike; and (4) Sengyokaidou, which represent urban river, urban canal, urban lake, and built-up urban environment as a control group, respectively (Figure 1). See Table 1 for details of the vegetation and environmental features of the four study sites.

**Table 1.** Study sites profile.

| Site (Code in Figure 1) | Category | Features | Main Vegetation around the Site | Description |
|---|---|---|---|---|
| Sakagawa (B) | Urban River | Mainly vegetation and water bodies | *Quercus myrsinifolia; Zelkova serrata; Celtis sinensis; Cornus officinalis; Acorus calamus; Prunus subgen.Cerasus; Rhododendron; Hydrangea macrophylla* | Sakagawa is a river with a long history, originating in Kashiwa City and eventually flowing into the Edo River. There are many aquatic plants in the river, and many trees have been planted on both sides of the river, resulting in an area that is a blend of natural and artificial environments. |
| Shinsakagawa (C) | Urban Canal | Mainly water bodies and buildings | *Parthenocissus tricuspidate; Rhododendron; Hydrangea macrophylla; Quercus myrsinifolia; Cornus officinalis* | An artificial waterway located in the center of Matsudo City. It is an engineered channel built for drainage management, and the river is lined mainly with commercial buildings and residential houses. This area has little vegetation or natural elements and is therefore a highly artificial environment. |
| Osagamicyousetuike (A) | Urban Lake | Mainly water bodies | | It is located in Koshigaya City, Saitama Prefecture, and is a reservoir (with a capacity of 1.2 million cubic meters of water) designed to resist urban flooding. As part of the Koshigaya Lake City business district, it is surrounded by commercial buildings and residential communities. It is also a highly artificial environment where many visitors and residents come to walk and relax every day. |

**Table 1.** *Cont.*

| Site (Code in Figure 1) | Category | Features | Main Vegetation around the Site | Description |
|---|---|---|---|---|
| Sengyokaidou (D) | Control Group | Mainly buildings | | Sengyokaidou, as a control group, is a street located in the central urban area of Matsudo City, which is used by many pedestrians and vehicles every day. It only has a small amount of vegetation and does not contain any water bodies, so it is a completely built-up urban environment. |

**Figure 1.** (Red box) The location of the study sites; (A) Osagamicyousetuike, (B) Sakagawa, (C) Shinsakagawa, (D) Sengyokaidou.

### *2.2. Study Sample*

We performed "within-subject" experiments. Invitations were sent via social media software (LINE and WeChat) and 50 students were recruited from the Department of Horticulture at Chiba University. The recruitment message required that the subjects be non-smokers, not have any mental illness, and be physically functioning. However, nine students were excluded because they indicated that they were unable to participate in the entire experiment. A final sample of 41 students (19 males and 22 females; Table 2) was

recruited, and all students visited the four experimental sites. The study was conducted according to the guidelines of the Declaration of Helsinki and with the approval of the Research Ethics Committee of the Institute of Horticulture, Chiba University (approval code: 21-05; 2021). Subjects were fully informed of the purpose and procedures involved and signed a consent form prior to the experiment. All participants were asked to abstain from alcohol and smoking for 24 h before the experiment.

**Table 2.** Subject information.

| Information | Value (Mean ± SD) |
|---|---|
| Male | 19 |
| Female | 22 |
| Age | 26.8 ± 2.9 |
| Weight (Kg) | 59.1 ± 11.2 |
| Height (cm) | 168.1 ± 8.7 |
| BMI (Kg/m$^2$) | 20.8 ± 2.5 |

### *2.3. Measurements*

During the experiment, several psychological scales were used to measure participants' self-reported restorative experiences, subjective vitality, and emotional states. All scales were measured using a seven-point Likert scale, ranging from 1 (not at all) to 7 (completely).

First, the Restoration Outcome Scale (ROS) was used to measure restorative experiences [36] and contains six items, three of which measure relaxation and calmness ("I feel restored and released", "I feel very calm", and "I grow enthusiastic and energetic about my daily life"), one item reflects restored attention ("I feel focused"), and the other two reflect clearing one's thoughts ("I can forget my daily worries" and "My thoughts are clear").

The Subjective Vitality Scale (SVS) [37] contains five items to measure self-reported feelings of vitality and being alive: "I feel alive and vital", "I feel very energetic", "I look forward to each new day", "I feel alert and awake", and "I feel so alive I just want to burst".

Positive and negative affect are measured by the self-reported Positive and Negative Affect Scale (PANAS) [38]. The PANAS test contains two scales reflecting positive affect (PANAS POS) and negative affect (PANAS NEG). Both scales consist of ten items (Positive: Enthusiastic, Interested, Strong, Excited, Proud, Attentive, Inspired, Determined, Alert, Active; Negative: Distressed, Upset, Guilty, Scared, Hostile, Irritable, Ashamed, Nervous, Jittery, Afraid).

Finally, different levels of perceived natural elements (i.e., green, blue) may lead to different psychological recovery effects [17,39,40]. Therefore, based on previous studies [17,41], two additional questions were sent to participants about their perception of natural element levels in the three UBSs: "To what extent can you perceive the level of green here? including various vegetation and aquatic plants", and "To what extent can you perceive the proportion of water bodies in the whole site here?" Participants were asked to respond to these two questions using a Likert scale of 1 (not at all) to 7 (very high). The overall perceived natural element level was the average of these two items.

### *2.4. Experimental Procedure*

The study procedures of Simkin et al. (2020) [35] and Tyrväinen et al. (2014) [30] were referenced. To eliminate order effects, all four experimental sites were visited in random order and on random days. To ensure the validity of the study, a within-subjects design was used, with each participant visiting one site per week and all participants visiting all four settings. The specific dates and times of the experiment were organized according to their own schedules, as participants may be required to attend classes or work part-time. The first round of experiments (25 samples) was conducted from 10 October to 20 November 2021, and the second round of experiments (16 samples) was conducted from April 20 to 20 May 2022 (autumn and spring were chosen because of the hot summers and cold winters in Japan). The time periods for each experiment were 9:00 a.m. to 11:00 a.m. and 1:00 p.m.

to 3:00 p.m. To eliminate external disturbances, similar weather conditions were chosen to conduct the experiments. In addition, the experimenters carried instruments to record environmental conditions, including humidity, temperature, light, and noise, every three minutes during the experiments. These values were not analyzed further and were only used for experimental condition reference (Table 3).

**Table 3.** Comparison of the environmental factors of the four environmental sites (M ± SD).

| Parameter | Urban River | Urban Canal | Urban Lake | Control Group |
|---|---|---|---|---|
| Temperature (°C) | 23.09 (±2.22) | 22.62 (±1.36) | 22.96 (±1.68) | 23.44 (±1.43) |
| Humidity (%) | 38.63 (±4.49) | 35.38 (±7.23) | 33.25 (±4.73) | 32.25 (±4.92) |
| Absolute illumination (lx) | 43,539 (±8051) | 50,331 (±2492) | 50,774 (±2476) | 55,945 (±5001) |
| Noise (dB) | 50.81 (±5.85) | 50.55 (±3.27) | 44.66 (±2.89) | 63.13 (±3.90) |

Figure 2 illustrates the process for a single experimental site, which was the same for all four sites. Participants were placed in a waiting room to rest upon arrival at the experimental site, and the experimental assistant introduced the experimental procedure to them. Subsequently, basic information about the subjects was collected (only before the first experiment) and the participants signed a written consent form for voluntary participation. After completion of the first questionnaire (ROS, SVS, and PANAS), the subjects were taken to the experimental site to commence the experiment. The group size for each trial was kept small, with a maximum of six people and a minimum of one person at a time, to minimize the influence of participants on each other. They were asked to focus on their own experience, remain quiet throughout the experiment, not talk to others, and not check their cellphones. The first phase of the experiment involved sitting in a chair in the field for 15 min to observe the environment of the site (Figure 3). After viewing, participants filled out a second questionnaire (ROS and SVS). The viewing phase was followed by a 15-min slow walk (Figure 4) led by a research assistant to ensure that all groups walked the same route (approximately 550 m long at each location) at the same speed. Participants were asked to walk in a line, retaining at least two meters between each other to avoid interfering with themselves. Simultaneously, another experimental assistant followed the group with an instrument to measure environmental factors. After the walk, participants returned to the waiting room and completed a third questionnaire (ROS, SVS, PANAS, and perceived natural element level). The whole experiment took about an hour, and participants were informed that they could withdraw from the experiment at any time.

### *2.5. Statistical Analysis*

A one-way analysis of variance (ANOVA) was performed to calculate the differences in each psychological indicator before the intervention (T1) and between genders. Moreover, non-metric multidimensional scaling (NMDS) with the Raup-Crick index as a distance metric revealed the overall pattern of the data and described the differences and similarities of participants in different study settings (different types of UBSs) [42]. The NMDS and the multi-response permutation procedure (MRPP) were run in R to validate the study settings (different types of UBSs) and to initially explore the variability between data from different sites. NMDS is a method of condensing information from multiple variables into a two-dimensional representation, where the closer the samples in the sorted space, the more similar their properties [43]. MRPP is used to complement the differences between test samples, where more negative T-values indicate greater differences between groups [44]. Both NMDS and MRPP are executed through the vegan package in R version 4.1.2 [45].

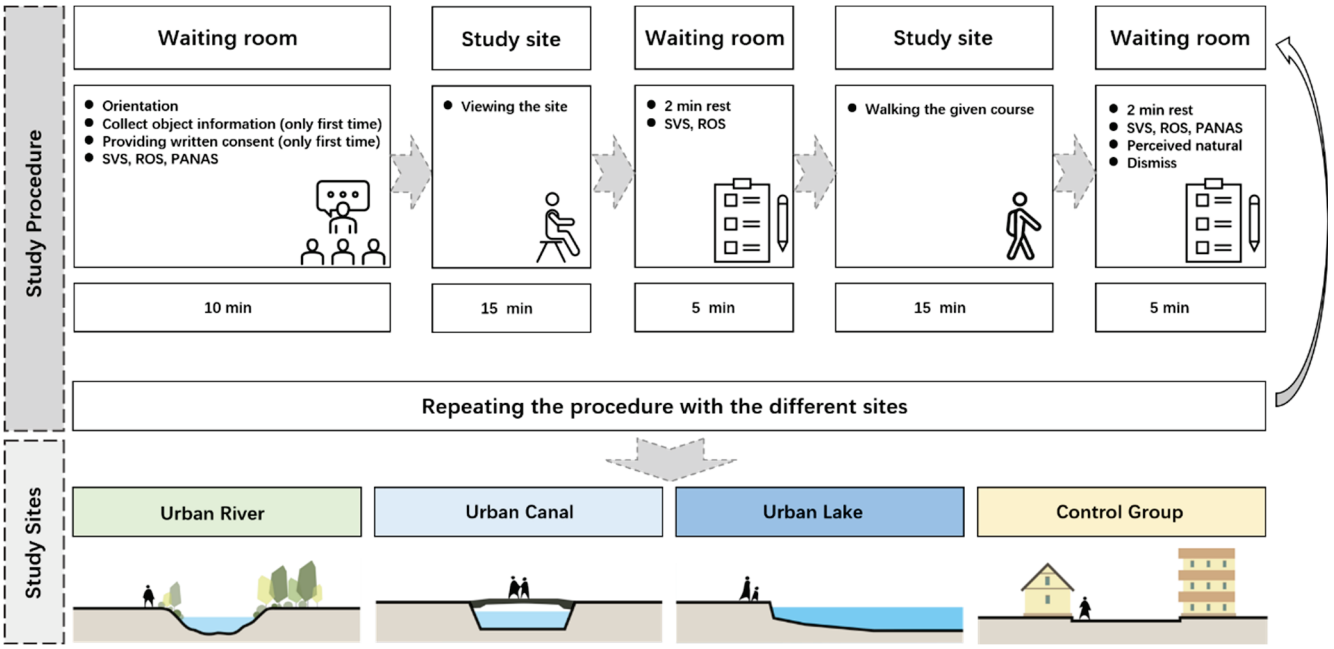



**Figure 2.** Experimental procedures.

**Figure 3.** Viewing session in the study sites (authorized photos). (**a**) Sakagawa, (**b**) Shinsakagawa, (**c**) Osagamicyousetuike, (**d**) Sengyokaidou.

**Figure 4.** Walking session in the study sites (authorized photos). (**a**) Sakagawa, (**b**) Shinsakagawa, (**c**) Osagamicyousetuike, (**d**) Sengyokaidou.

Repeated-measures ANOVA were then used to calculate the effects of the intervention on the four different environmental settings. First, four different sites (coded Place, i.e., Urban River, Urban Canal, Urban Lake, and Control Group) and three intervention time points (coded Time, i.e., before the experiment (T1), after viewing (T2), and after walking (T3)) were used as independent variables for main effects and interaction effects analyses. The purpose of this step was to compare the differences in psychological indicators under the influence of a single variable. Next, simple effects analysis was performed on indicators that interacted significantly with "Place" and "Time" to further compare differences in indicators under different combinations of the two variables (Place and Time). Finally, for the three UBS levels of perceived natural elements (blue, green, total), the Kruskal-Wallis H test (with post hoc test) was used to determine if there was a significant difference between the three data groups.

The SPSS v.20 (IBM, Armonk, NY, USA) software was used for all analyses. In all cases, *p*-values less than 0.05 were considered statistically significant. To calculate the minimum observed sample size required for the repeated-measures ANOVA, an a priori power analysis was performed using G*Power [46]. We set up four groups and four response variables per group and achieved 95% statistical power at the alpha level of 0.05. The results indicate that a minimum of 144 observation samples is required to achieve a moderate global effect with $f^2(V) = 0.0625$. Thus, in total, a sample of 164 observations from 41 volunteers at 4 sites was used as the final experimental data for analysis.

## 3. Results

### *3.1. Scale Statistics*

One-way ANOVA results showed no statistically significant differences for four psychological indicators between males and females at T1 time point (Appendix A Table A1), indicating that it was acceptable to analyze females and males together. Moreover, no statistically significant differences between sites for each psychological indicator before the intervention (T1) were found: SVS ($F_{(3,160)} = 0.211$, $p = 0.889$), ROS ($F_{(3,160)} = 1.120$, $p = 0.343$), PANAS POS ($F_{(3,160)} = 0.907$, $p = 0.439$), PANAS NEG ($F_{(3,160)} = 0.371$, $p = 0.774$). This indicates that the experimental procedure was acceptable because there was no significant difference in the participants' pre-experimental status (T1) and therefore the data from T2 and T3 were able to be used for subsequent analysis.

Table 4 demonstrates the scale statistics. Cronbach's α values were good for all scales, ranging from 0.73 to 0.96, with only one data point having a lower but acceptable reliability score (SVS ($_{T2, CG}$) = 0.60). For all psychological indicators, mean sum scores were calculated. Furthermore, the correlation matrix between the four psychological indicators for the three time points is shown in Appendix A Table A2. Only the correlations within each time

point were observed. SVS and ROS were significantly positively correlated at all time points in all experimental sites. SVS, ROS, and PANAS POS were significantly positively correlated at T1 and T3 time points in all experimental sites. Not surprisingly, PANAS NEG showed negative correlations with the other three indicators, but in a few cases, this relationship was not statistically significant ($p > 0.05$). The correlation results suggest that the scale data from the four experimental sites fit the scale characteristics, as the SVS, ROS, and PANAS POS scales represent positive psychological states, whereas the PANAS NEG reflects negative psychological states, and an increase in PANAS NEG values would lead to a decrease in other scale evaluations. Therefore, it was preliminarily determined that the results of the four scales in all experimental sites were able to correctly reflect the participants' psychological states at the corresponding time points (T1–T3).

**Table 4.** Data of all psychological scales at the four experimental sites (164 observation samples).

| **Place** | **UR (N = 41)** | | | **UC (N = 41)** | | | **UL (N = 41)** | | | **CG (N = 41)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Measures** | **M** | **SD** | **α** | **M** | **SD** | **α** | **M** | **SD** | **α** | **M** | **SD** | **α** |
| Before the experiment (T1) | | | | | | | | | | | | |
| SVS | 4.18 | 1.03 | 0.88 | 4.01 | 1.00 | 0.85 | 4.10 | 0.84 | 0.80 | 4.04 | 1.05 | 0.84 |
| ROS | 4.24 | 0.98 | 0.89 | 3.93 | 0.90 | 0.88 | 3.89 | 0.97 | 0.87 | 4.05 | 0.91 | 0.84 |
| PANAS POS | 4.06 | 0.78 | 0.88 | 3.78 | 0.97 | 0.94 | 3.88 | 1.01 | 0.91 | 3.76 | 0.92 | 0.91 |
| PANAS NEG | 2.37 | 0.89 | 0.93 | 2.29 | 0.96 | 0.93 | 2.20 | 1.10 | 0.96 | 2.16 | 0.90 | 0.93 |
| After viewing (T2) | | | | | | | | | | | | |
| SVS | 4.74 | 1.05 | 0.83 | 4.42 | 0.93 | 0.73 | 4.35 | 1.03 | 0.81 | 3.95 | 0.93 | 0.60 |
| ROS | 5.39 | 1.19 | 0.93 | 4.85 | 1.11 | 0.91 | 5.03 | 1.06 | 0.90 | 3.58 | 1.24 | 0.91 |
| After walking (T3) | | | | | | | | | | | | |
| SVS | 4.62 | 0.97 | 0.78 | 4.63 | 1.00 | 0.77 | 4.44 | 1.09 | 0.79 | 4.15 | 0.97 | 0.76 |
| ROS | 5.06 | 1.29 | 0.95 | 4.85 | 1.20 | 0.93 | 5.02 | 1.20 | 0.93 | 3.65 | 1.13 | 0.90 |
| PANAS POS | 4.64 | 1.02 | 0.92 | 4.53 | 1.03 | 0.91 | 4.59 | 1.04 | 0.91 | 3.74 | 0.94 | 0.89 |
| PANAS NEG | 1.78 | 0.78 | 0.93 | 1.64 | 0.64 | 0.91 | 1.57 | 0.82 | 0.96 | 2.45 | 1.20 | 0.95 |

Note. UR, Urban River; UC, Urban Canal; UL, Urban Lake; CG, Control Group; M, mean value; SD, standard deviation; α, Cronbach's α.

### *3.2. The NMDS and MRPP Results*

Referring to a previous study [42], NMDS and MRPP were run in R to validate the study setting (different types of UBSs) and to initially explore the variability between data from different sites. NMDS results based on a sample of 164 observations from four experimental sites show similarities between the results of the UC, UL, and UR and distinguishes them from those of the CG. Our analysis results showed that there was a statistically significant difference when participants described the environment perception between CG and the other three UBSs. Specially, MRPP results indicated significant differences between CG and UC (T-value = −8.327, $p = 0.001$), UL (T-value = −10.389, $p = 0.001$), and UR (T-value = −12.573, $p = 0.001$). The statistical results suggest that the environment perception of participants at the urban environment (CG) varied from the environment perception in the other three UBSs. It is worth noticing that the most significant difference of restorative perception was urban environment (CG) and urban river (UR), followed by urban lake (UL). In contrast, the perceived differences between the control group and the urban canal (UC) were smaller than the other two UBSs (Figure 5).

### *3.3. The Repeated-Measures ANOVA Results*

A repeated measures ANOVA was performed (Table 5). For the analyses, we used four within-subject factors (Urban River (UR), Urban Canal (UC), Urban Lake (UL), and Control Group (CG)). Additionally, three intervention time points (before the experiment (T1), after viewing (T2), and after walking (T3)) were used for SVS and ROS, while the PANAS POS and PANAS NEG scales were tested only at T1 and T3.

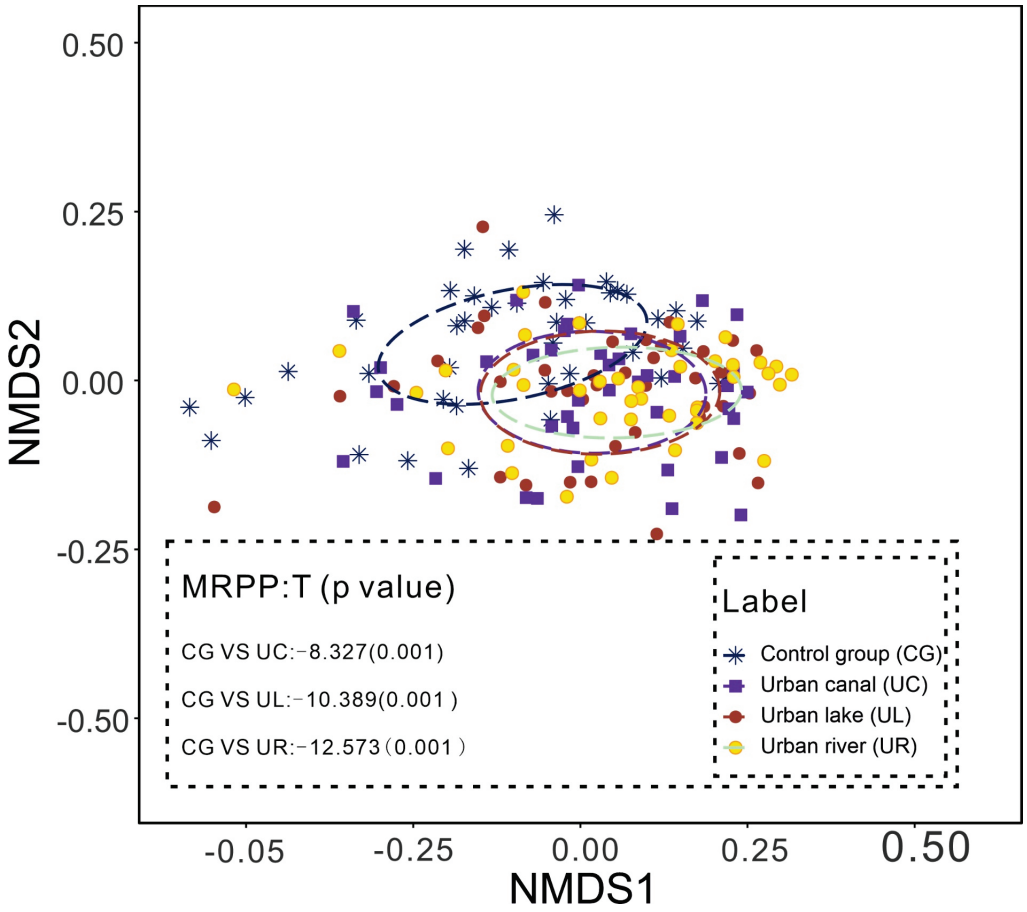



**Figure 5.** NMDS and MRPP results of 164 observation samples. The ellipse in the figure indicates the standard deviation. T describes the size of the difference, and the larger the absolute value of T, the greater the difference. Different colored dots represent different experimental sites.

**Table 5.** Main effect and interaction effect of experimental sites and time on SVS, ROS, PANAS POS, and PANAS NEG (164 observation samples).

| Indicators | Sum of Squares | df | Mean Square | F | Sig. | Partial $\eta^2$ | Pairwise Comparisons |
|---|---|---|---|---|---|---|---|
| SVS (score) | | | | | | | |
| Constant | 9106.542 | 1 | 9106.542 | 8992.726 | 0.000 | 0.949 | |
| Place | 13.991 | 3 | 4.664 | 4.605 | 0.003 ** | 0.028 | UR, UC, UL > CG |
| Time | 12.753 | 2 | 6.376 | 6.297 | 0.002 ** | 0.026 | T3, T2 > T1 |
| Place × Time | 6.048 | 6 | 1.008 | 0.995 | 0.428 | 0.012 | |
| Error | 486.075 | 480 | 1.013 | | | | |
| (Adj R2 = 0.201) | | | | | | | |
| ROS (score) | | | | | | | |
| Constant | 9797.722 | 1 | 9797.722 | 7821.063 | 0.000 | 0.942 | |
| Place | 88.706 | 3 | 29.569 | 23.603 | 0.000 ** | 0.129 | UR, UL > UC > CG |
| Time | 46.839 | 2 | 23.420 | 18.695 | 0.000 ** | 0.072 | T3, T2 > T1 |
| Place × Time | 45.443 | 6 | 7.574 | 6.046 | 0.000 ** | 0.070 | |
| Error | 601.313 | 480 | 1.253 | | | | |
| (Adj R2 = 0.314) | | | | | | | |
| PANAS POS (score) | | | | | | | |
| Constant | 5569.581 | 1 | 5569.581 | 5806.570 | 0.000 | 0.948 | |
| Place | 16.724 | 3 | 5.575 | 5.812 | 0.001 ** | 0.052 | UR, UC, UL > CG |
| Time | 20.801 | 1 | 20.801 | 21.686 | 0.000 ** | 0.063 | T3 > T1 |
| Place × Time | 7.675 | 3 | 2.558 | 2.667 | 0.048 * | 0.024 | |
| Error | 306.940 | 320 | 0.959 | | | | |
| (Adj R2 = 0.209) | | | | | | | |

**Table 5.** *Cont.*

| Indicators | Sum of Squares | df | Mean Square | F | Sig. | Partial $\eta^2$ | Pairwise Comparisons |
|---|---|---|---|---|---|---|---|
| PANAS NEG (score) | | | | | | | |
| Constant | 1391.159 | 1 | 1391.159 | 1576.624 | 0.000 | 0.831 | |
| Place | 8.024 | 3 | 2.675 | 3.031 | 0.030 * | 0.028 | CG > UR, UL, UC |
| Time | 12.684 | 1 | 12.684 | 14.375 | 0.000 ** | 0.043 | T1 > T3 |
| Place × Time | 12.906 | 3 | 4.302 | 4.876 | 0.002 ** | 0.044 | |
| Error (Adj R2 = 0.217) | 282.357 | 320 | 0.882 | | | | |

Note. UR, Urban River; UC, Urban Canal; UL, Urban Lake; CG, Control Group; * $p < 0.05$, ** $p < 0.01$.

For SVS, there was a significant main effect of experimental sites on the scores of subjective vitalities, $F_{Place} = 4.605$, $p = 0.003$, Partial $\eta^2 = 0.028$ (Table 5). Paired comparison results indicated that urban river (M = 4.51), urban canal (M = 4.36), and urban lake (M = 4.30) were equal in measure and higher than urban environments (control group, M = 4.04) (Figure 6a). There was also a significant main effect of time, $F_{Time} = 6.297$, $p = 0.002$, Partial $\eta^2 = 0.026$ (Table 5). Comparisons showed that scores for T2 (M = 4.37) and T3 (M = 4.46) were significantly greater than T1 (M = 4.08) (Figure 6b), indicating that both viewing and walking behaviors positively influenced participants' subjective vitalities. Furthermore, the insignificant interaction effect ($F_{Place \times Time} = 0.995$, $p = 0.428$, Partial $\eta^2 = 0.012$, Figure 7a) indicates that no significant differences were shown between the exposure results of two different behaviors (viewing and walking) performed in the four experimental sites.

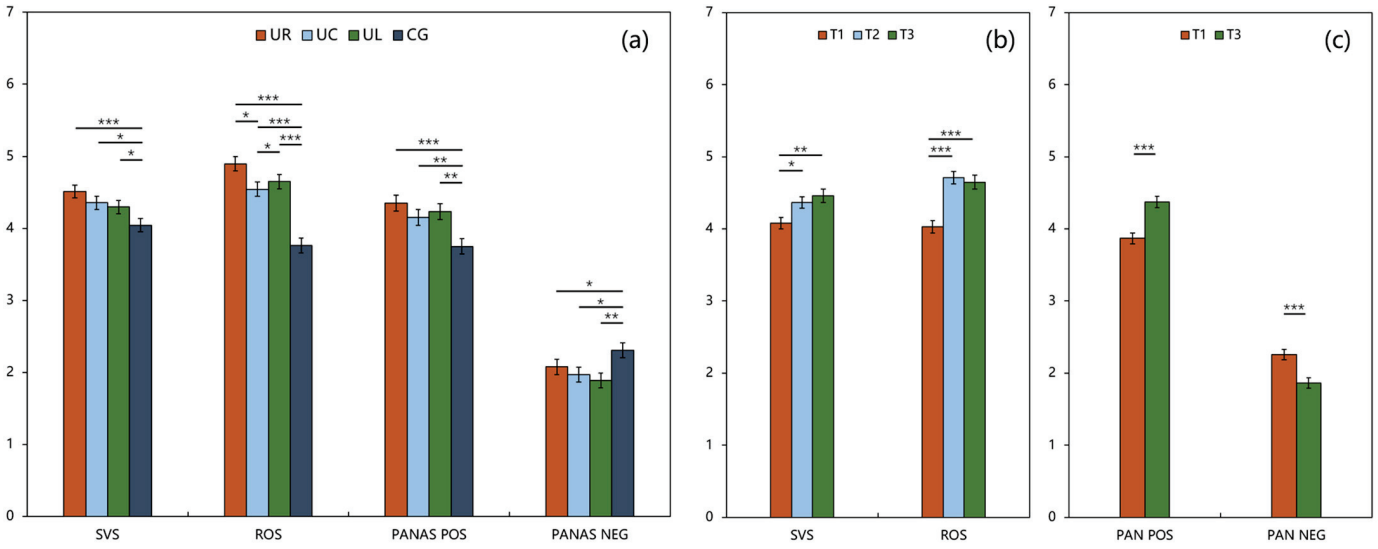



**Figure 6.** SVS, ROS, PANAS POS, and PANAS NEG in the main effects analysis (mean ± standard error; UR, Urban River; UC, Urban Canal; UL, Urban Lake; CG, Control Group; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). (**a**) Main effect of Place (SVS, ROS, PANAS POS), (**b**) Main effect of Time (SVS, ROS), (**c**) Main effect of Time (PAN POS, PAN NEG).

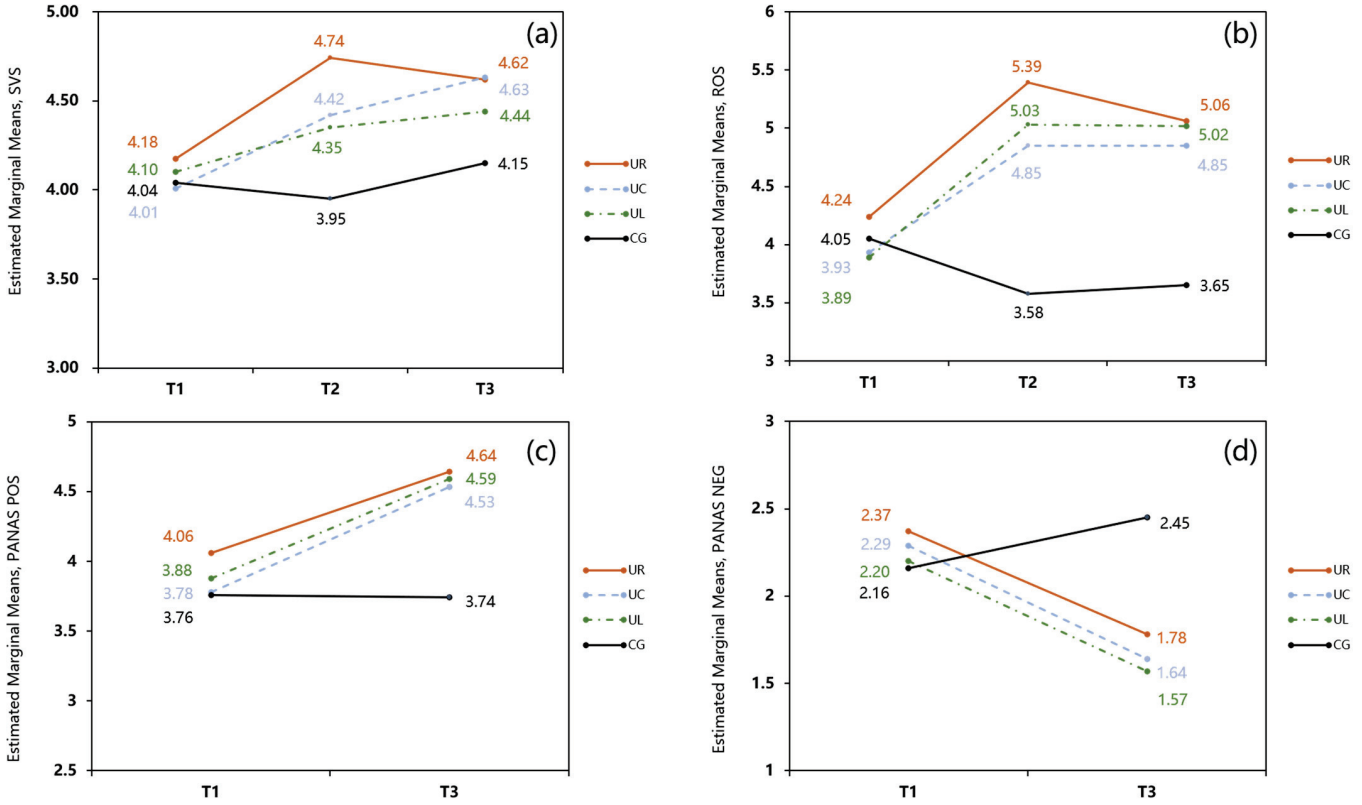



**Figure 7.** Interaction graphs for SVS (**a**), ROS (**b**), PANAS POS (**c**), and PANAS NEG (**d**); UR, Urban River; UC, Urban Canal; UL, Urban Lake; CG, Control Group.

For ROS, there was a significant main effect of experimental sites on the restorative outcome scores, $F_{Place}$ = 23.603, $p < 0.001$, Partial $\eta^2$ = 0.129 (Table 5). Paired comparison results indicated that urban river (M = 4.90) and urban lake (M = 4.65) were equally restorative and more restorative than urban canal (M = 4.54) and urban environments (M = 3.76) (Figure 6a). There was also a significant main effect of time on the restorative outcome scores, $F_{Time}$ = 18.695, $p < 0.001$, Partial $\eta^2$ = 0.072 (Table 5). Comparisons showed that scores for T2 (M = 4.71) and T3 (M = 4.65) were significantly greater than T1 (M = 4.02) (Figure 6b), indicating that both viewing and walking behaviors positively influenced participants' perceptions of restoration. Furthermore, the significant interaction effect of time and place ($F_{Place \times Time}$ = 6.046, $p < 0.001$, Partial $\eta^2$ = 0.070, Table 5) indicated that the subjects felt recovery in different ways at different times and sites. Simple effects (Table 6) analyses were performed separately for place and time, and the results indicated that place differed significantly at time points T2 (UR (M = 5.39), UL (M = 5.03) > UC (M = 4.85) > CG (M = 3.58)) and T3 (UR (M = 5.06), UL (M = 5.03), UC (M = 4.85) > CG (M = 3.65)) (Figure 7b), which suggests that the restorative effect of viewing in UR and UL for 15 min was significantly stronger than in UC and CG, while the restorative effect of walking was significantly higher in all three UBS than in the urban environment. Time was significantly different across the three experimental sites in urban river (T3 (M = 5.06), T2 (M = 5.39) > T1 (M = 4.24)), urban canal (T3 (M = 4.85), T2 (M = 4.85) > T1 (M = 3.93)), and urban lake (T3 (M = 5.02), T2 (M = 5.03) > T1 (M = 3.89)) (Table 6, Figure 7b), suggesting that 15 min of viewing as well as 15 min of walking at all three UBSs significantly and positively influenced restorative scores. No significant effects were caused after viewing and walking in the urban setting.

**Table 6.** Simple-effects analysis of the indicators that have significant interaction effects on ROS, PANAS POS, and PANAS NEG.

| Indicators | Sum of Squares | df | Mean Square | F | Sig. | Partial $\eta^2$ | Pairwise Comparisons |
|---|---|---|---|---|---|---|---|
| ROS (score) | | | | | | | |
| Place (Time = T1) | 3.038 | 3 | 1.013 | 0.808 | 0.490 | 0.005 | |
| Error | 601.313 | 480 | 1.253 | | | | |
| Place (Time = T2) | 76.100 | 3 | 25.367 | 20.249 | 0.000 ** | 0.112 | UR, UL > UC > CG |
| Error | 601.313 | 480 | 1.253 | | | | |
| Place (Time = T3) | 55.012 | 3 | 18.337 | 14.638 | 0.000 ** | 0.084 | UR, UC, UL > CG |
| Error | 601.313 | 480 | 1.253 | | | | |
| Time (Place = UR) | 28.745 | 2 | 14.373 | 11.473 | 0.000 ** | 0.046 | T3, T2 > T1 |
| Error | 601.313 | 480 | 1.253 | | | | |
| Time (Place = UC) | 23.072 | 2 | 11.536 | 9.209 | 0.000 ** | 0.037 | T3, T2 > T1 |
| Error | 601.313 | 480 | 1.253 | | | | |
| Time (Place = UL) | 35.282 | 2 | 17.641 | 14.082 | 0.000 ** | 0.055 | T3, T2 > T1 |
| Error | 601.313 | 480 | 1.253 | | | | |
| Time (Place = CG) | 5.183 | 2 | 2.592 | 2.069 | 0.127 | 0.009 | |
| Error | 601.313 | 480 | 1.253 | | | | |
| PANAS POS (score) | | | | | | | |
| Place (Time = T1) | 2.378 | 3 | 0.793 | 0.826 | 0.480 | 0.008 | |
| Error | 306.940 | 320 | 0.959 | | | | |
| Place (Time = T3) | 22.020 | 3 | 7.340 | 7.652 | 0.000 ** | 0.067 | UR, UC, UL > CG |
| Error | 306.940 | 320 | 0.959 | | | | |
| Time (Place = UR) | 6.792 | 1 | 6.792 | 7.081 | 0.008 ** | 0.022 | T3 > T1 |
| Error | 306.940 | 320 | 0.959 | | | | |
| Time (Place = UC) | 11.494 | 1 | 11.494 | 11.983 | 0.001 ** | 0.036 | T3 > T1 |
| Error | 306.940 | 320 | 0.959 | | | | |
| Time (Place = UL) | 10.185 | 1 | 10.185 | 10.619 | 0.001 ** | 0.032 | T3 > T1 |
| Error | 306.940 | 320 | 0.959 | | | | |
| Time (Place = CG) | 0.004 | 1 | 0.004 | 0.005 | 0.946 | 0.000 | |
| Error | 306.940 | 320 | 0.959 | | | | |
| PANAS NEG (score) | | | | | | | |
| Place (Time = T1) | 1.069 | 3 | 0.356 | 0.404 | 0.750 | 0.004 | |
| Error | 282.357 | 320 | 0.882 | | | | |
| Place (Time = T3) | 19.861 | 3 | 6.620 | 7.503 | 0.000 ** | 0.066 | CG > UR, UC, UL |
| Error | 282.357 | 320 | 0.882 | | | | |
| Time (Place = UR) | 7.024 | 1 | 7.024 | 7.961 | 0.005 ** | 0.024 | T1 > T3 |
| Error | 282.357 | 320 | 0.882 | | | | |
| Time (Place = UC) | 8.629 | 1 | 8.629 | 9.779 | 0.002 ** | 0.030 | T1 > T3 |
| Error | 282.357 | 320 | 0.882 | | | | |
| Time (Place = UL) | 8.181 | 1 | 8.181 | 9.271 | 0.003 ** | 0.028 | T1 > T3 |
| Error | 282.357 | 320 | 0.882 | | | | |
| Time (Place = CG) | 1.756 | 1 | 1.756 | 1.990 | 0.159 | 0.006 | |
| Error | 282.357 | 320 | 0.882 | | | | |

Note. UR, Urban River; UC, Urban Canal; UL, Urban Lake; CG, Control Group; ** $p < 0.01$.

For PANAS POS, there was a significant main effect of experimental sites on positive emotions, $F_{Place} = 5.812$, $p = 0.001$, Partial $\eta^2 = 0.052$ (Table 5). Paired comparison results indicated that urban river (M = 4.35), urban canal (M = 4.15), and urban lake (M = 4.23) have higher positive emotions than urban environments (M = 3.75) (Figure 6a). Additionally, there was a significant main effect of time on positive emotions, $F_{Time} = 21.686$, $p < 0.001$, Partial $\eta^2 = 0.063$ (Table 5). Comparisons showed that scores for T3 (M = 4.37) were significantly greater than for T1 (M = 3.87) (Figure 6b), suggesting that a 15-min walk improved participants' positive emotions. Furthermore, the significant interaction effect of time and place ($F_{Place \times Time} = 2.667$, $p = 0.048$, Partial $\eta^2 = 0.024$, Table 5) indicated that the subjects felt emotion improvement in different ways at different times and sites. Simple effects (Table 6) results indicated that place differed significantly at time points T3 (UR (M = 4.64), UL (M = 4.59), UC (M = 4.53) > CG (M = 3.74)) (Figure 7c), which suggests that the emotion improvement effect of walking in UR, UC, and UL for 15 min was significantly stronger than in CG. Time was significantly different across the three

experimental sites in UR (T3(M = 4.64) > T1(M = 4.06)), UC (T3(M = 4.53) > T1(M = 3.78)), UL (T3(M = 4.59) > T1(M = 3.88)) (Table 6, Figure 7c), suggesting that 15 min of walking at all three UBSs positively influenced the positive emotions of the participants. No significant effects were caused after walking in the CG (T3(M = 3.74), T1(M = 3.76), $p = 0.127$, Table 6, Figure 7c).

With PANAS NEG, a significant main effect of the experimental site on negative emotions was found, $F_{Place} = 3.031$, $p = 0.030$, Partial $\eta^2 = 0.028$. Paired comparison results indicated that urban river (M = 2.076), urban canal (M = 1.968), and urban lake (M = 1.889) were lower than urban environments (M = 2.31) (Figure 6a). There was a significant main effect of time on negative affect, $F_{Time} = 14.375$, $p < 0.001$, Partial $\eta^2 = 0.043$ (Table 5). Pairwise comparisons showed that scores for T1 (M = 2.26) were significantly greater than those for T3 (M = 1.86) (Figure 6b), indicating that the 15-min walk was effective in reducing participants' negative emotions. Moreover, the interaction effect of time and place was statistically significant ($F_{Place \times Time} = 4.876$, $p = 0.002$, Partial $\eta^2 = 0.044$, Table 5). Simple effects results showed that place differed significantly at time points T3 (UR (M = 1.78), UC (M = 1.64), UL (M = 1.57) < CG (M = 2.45)), time at urban river (T3 (M = 1.78) < T1 (M = 2.37)), time at urban canal (T3 (M = 1.64) < T1 (M = 2.29)), and time at urban lake (T3(M = 1.57) < T1(M = 2.20)), with significant differences among the three UBSs (Table 6, Figure 7d). This suggests that walking for 15 min in the three UBSs has a significantly stronger effect on the improvement of negative emotions than the urban environment (control group).

### *3.4. Natural Element Level Perception of Three UBSs*

The final part of the questionnaire collected participants' perceived natural element levels of the three urban blue spaces. Figure 8 and Table 7 show the differences in the perceived natural element levels between the three UBSs, as well as the results and effect sizes of the Kruskal-Wallis H test (with post hoc test). According to the results, perceived blue levels were highest in Urban Lake (6.34 ± 0.52) and significantly higher than in Urban River (4.46 ± 1.47, adj $p < 0.001$) and Urban Canal (5.22 ± 0.98, adj $p < 0.001$), while no significant differences were found between Urban River and Urban Canal (adj $p = 0.157$). For perceived green levels, Urban River was the highest (6.34 ± 1.20) and significantly higher than Urban Canal (3.20 ± 1.47, adj $p < 0.001$) and Urban Lake (3.34 ± 1.39, adj $p < 0.001$), while no significant differences were found between Urban Lake and Urban Canal (adj $p = 1.000$). For total natural perception, Urban Canal (4.21 ± 1.02) was significantly lower than Urban River (4.80 ± 0.97, adj $p = 0.016$) and Urban Lake (4.84 ± 0.74, adj $p = 0.005$), while no significant differences were found between Urban Lake and Urban River (adj $p = 1.000$).

**Table 7.** Kruskal-Wallis H test (multiple comparisons) results with effect sizes.

| | | N | Test Statistic | df | Sig. | $\eta^2$ | Cohen's d |
|---|---|---|---|---|---|---|---|
| Perceive Blue | | 123 | 47.121 | 2 | <0.001 | 0.376 | 1.553 |
| | UR vs. UC | 41 | −14.659 | | 0.157 | | |
| | UR vs. UL | 41 | −50.427 | | <0.001 | | |
| | UC vs. UL | 41 | −35.768 | | <0.001 | | |
| Perceive Green | | 123 | 33.360 | 2 | <0.001 | 0.261 | 1.19 |
| | UC vs. UR | 41 | 40.146 | | <0.001 | | |
| | UL vs. UR | 41 | 36.866 | | <0.001 | | |
| | UC vs. UL | 41 | −3.280 | | 1.000 | | |
| Perceive of Total Nature | | 123 | 11.790 | 2 | 0.003 | 0.082 | 0.596 |
| | UC vs. UR | 41 | 21.707 | | 0.016 | | |
| | UC vs. UL | 41 | −24.354 | | 0.005 | | |
| | UR vs. UL | 41 | −2.646 | | 1.000 | | |

Note. UR, Urban River; UC, Urban Canal; UL, Urban Lake.

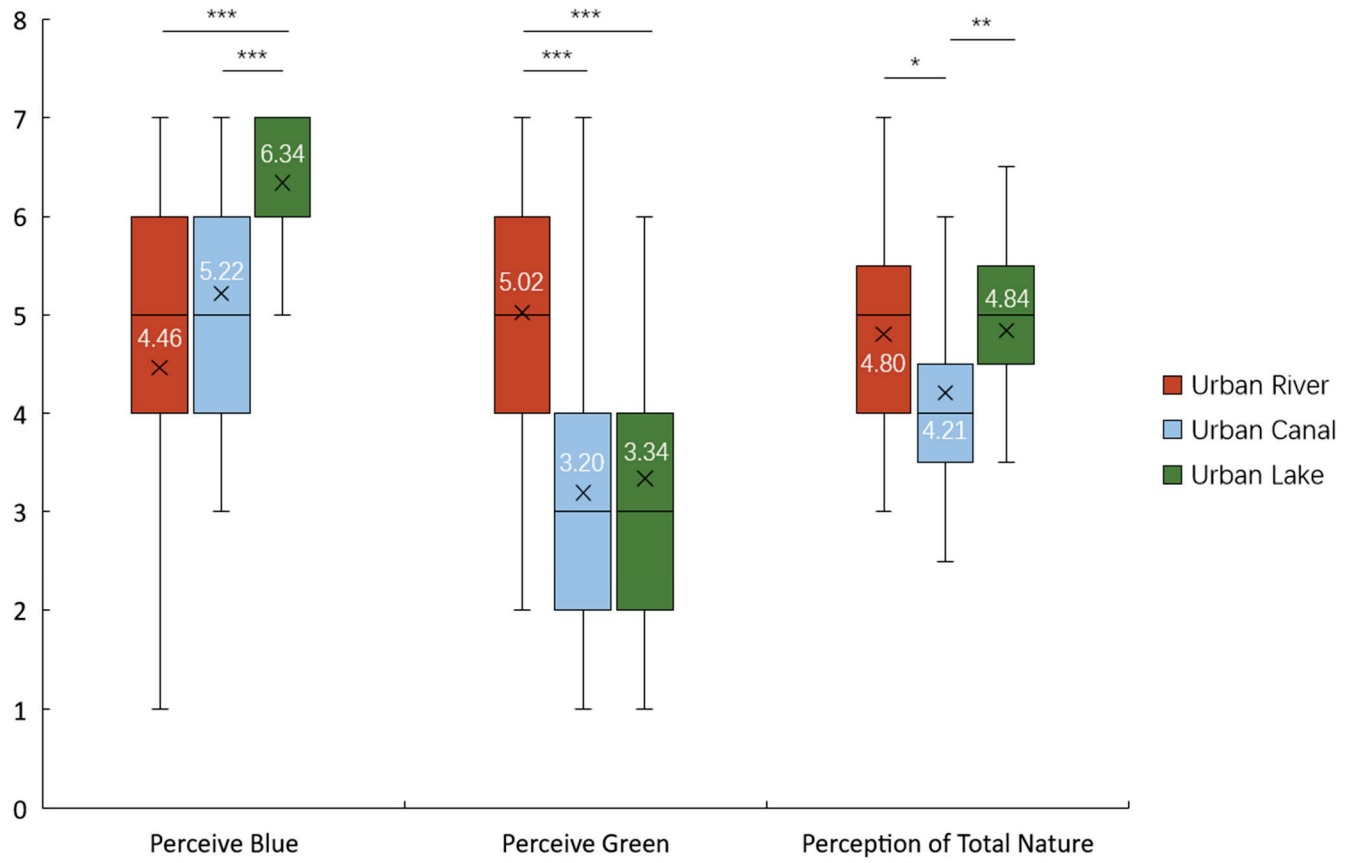



**Figure 8.** Difference results of perceived natural element levels in the three UBSs by Kruskal-Wallis H test. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. The "×" in the box represents the mean value.

## 4. Discussion

### *4.1. Summary of the Major Findings*

First, we investigated the effects of the four environmental settings on the subjects by using multiple psychological measures, which include Subjective Vitality (SVS) as an indicator of well-being and which has been conceptualized as a positive psychological state [47], the Restorative Outcome Scale (ROS) as a reliable scale developed based on previous research and observations of the restoration phenomenon [48], and improvements in emotion (PANAS) that have been consistently linked to psychological well-being [49]. In particular, higher SVS scores represented higher perceptions of subjective vitality; higher ROS scores represented greater perceived restorative outcomes (relaxation, calmness, concentration, and clarity of thought); higher PANAS POS scores and lower PANAS NEG scores represented better improvements in emotion.

In sum, all three UBSs increased vitality, feelings of restoration, and positive emotions, and decreased negative emotions; while the urban environment did not significantly improve these indicators. Consistent with the results of previous related studies [30,35,50], the results confirm that the restorative benefits of UBSs are similar to those of other green environments (e.g., urban parks, urban forests). Furthermore, no significant differences of mental restoration were observed between walking (T3) and viewing (T2) in the three UBSs. Moreover, taken together, the main effects of study sites showed that the urban river (UR) and the urban lake (UL) had the highest restorative scores, followed by the urban canal (UC), with the lowest in the control group (urban environment), confirming that different urban blue spaces may have different restorative outcomes. The reasons and implications of these findings will be discussed in depth in the following sections.

*4.2. Restorative Benefits Were Found at Different Time Points, but Not Significantly Different*

Previous research has demonstrated that spending time in blue spaces improves mental health, such as by viewing water bodies [21] and walking around a waterside [51]. So far, there has been a great deal of discussion about the causes of the mental restoration of blue space. One possible interpretation is from the perspective of evolutionary psychology; blue space provides humans with the natural space and resources (e.g., fresh water, food) they need to survive [52]. Second, according to Ulrich et al. (1991) [40], if an individual encounters a natural environment that is not threatening, there will be stress-reducing and restorative effects. The three UBSs we selected are all common types of water bodies in Japanese cities and are used daily by local residents in these areas. Therefore, for study subjects, unlike lakes in the wilderness or rivers in the forest, blue spaces in urban areas are less likely to feel threatening. Third, similar to numerous discussions of the restorative nature of green space, unconscious attention or fascination can lead to restorative impacts [39,40]. Thus, unlike the marine blue space, the freshwater blue space selected for this study was "soft" in that the water flow was gentle for the most part, with no rough waves to attract the subjects' voluntary attention, thus allowing participants' brains to relax and recover from mental fatigue. This can be particularly beneficial for individuals who are experiencing stress or mental exhaustion. Finally, Subiza-Pérez et al. (2019) stated that the sublime, a sense of connection to something larger than ourselves, can also be experienced even in daily natural environments such as urban blue spaces which can promote feelings of awe and wonder, which have been linked to positive emotions and well-being [7]. For example, in this study, the urban lake has a large body of water, and this large natural element in an urban environment may have surprised the subjects and evoked a sense of sublimity, thus leading to mental restoration.

However, it is interesting to see that there was not much difference between T2 and T3, suggesting that the mental restoration effects of walking and viewing in UBSs are the same. Previous studies have shown that the viewing stage is almost a psychological experience (sedentary), while the walking stage includes both the psychological and physical interactions with the landscapes, and the physical activity may also contribute to the restoration [30,35]. In this regard, we propose the following three possible explanations:

(1) Due to the plateau effect [53], the act of 15 min of viewing already caused subjects to perceive a high level of mental restoration. Therefore, a walking session (15 min of viewing combined with 15 min of physical activity) would hardly lead to a higher level of perceived mental recovery for the subjects compared to 15 min of viewing.
(2) Second, the health effects of physical activity typically come from a reduction in blood pressure and heart rate. However, a previous study showed that no positive cardiovascular effects were observed for the walking behavior in the blue space [54]. Therefore, we speculate that unlike the green space [31,34,55], the walking behavior in the UBS had a limited effect on physical health and therefore led to the same psychological recovery outcome as the 15 min viewing.
(3) Moreover, the exposure time was not sufficient. Both the viewing session and the walking session in the present study were 15 min, unlike two previous similar studies, which had 30 min walking sessions, leading to a higher level of recovery outcomes [30,35].

*4.3. The Restorative Effect of Different UBS Is Different*

Until recently, the restorativeness of different types of natural environments was still being discussed. Korpela et al. (2010) found that the restorative experiences of extensively managed natural areas (large forest areas, small-scale wooded areas) and built-up green spaces (large green lots, decorative plantations) were different [28]. An experiment in Finland showed that three old forests had stronger restorative effects compared to a young commercial forest [35]. Other studies have found different positive impacts on stress relief between large urban woodlands and intensively managed urban parks, although this difference is smaller [30]. Additionally, the green space type with the most natural elements (peri-urban green area) was found to be the most restorative, while the green space type

with predominantly built elements (urban square) was found to be the least restorative [29]. These findings all confirm the conclusion that even though thought to be restorative environments, the positive effects of different environmental settings are different.

Similarly, differences in the restorativeness of the three UBSs were found in the results of this study: the urban river as well as the urban lake were the most restorative, while the urban canal was less restorative. Reviewing the components of these environmental settings, UR is a blend of natural and artificial environments as many aquatic plants and street trees are planted, UL is a large artificial lake, and UC is an artificial waterway located in a built-up area which has a smaller water body area compared to UL. According to previous studies, higher perceived blue space and perceived green space within settlements are significantly associated with higher restorative quality [13], perceived restorativeness increases with increasing naturalness in green space [29], and there is a positive correlation between restorativeness scores and the proportion of water in the scene [17]. These findings all affirm that there is a positive relationship between the dose of natural elements in the scene and the intensity of the restorative experience [17,56].

Along these same lines, arguably, the higher the overall dose of visible/accessible natural elements in an environment, the higher the restorative quality of the environment, whether these natural elements are green (vegetation) or blue (water bodies), which is consistent with the Biophilia Hypothesis [57]. Accordingly, it appears possible to propose the concept of a "natural health dose" to emphasize the complementary effects of blue and green elements (Figure 9), which could explain why health outcomes may be different for different restorative environments. For example, compared to the UC, the UR had a similar level of visibility in its water bodies (in fact, the UC and UR are different areas of the same waterway, Figure 1), but the addition of many natural plants resulted in a significant increase in the overall total number of visible natural elements in the scene (Figure 8), which greatly enhanced the restorative effects of the environment. Similarly, both the UL and UC are highly artificial environments (the lower perceived green levels), but the UL has a larger area of water, so the subjects were able to observe a higher proportion of water in the scene (Figure 8), leading to a better restorative experience [17], which is perhaps also consistent with the coherence of the scene in Attention Restoration Theory [39]. However, as Jiang et al. (2014) [56] highlight the existence of a threshold of natural elemental dose to ensure moderate benefits, there is also a threshold of "natural health dose" for different blue spaces/blue-green spaces in the city, which will be another topic of continued discussion in the future.

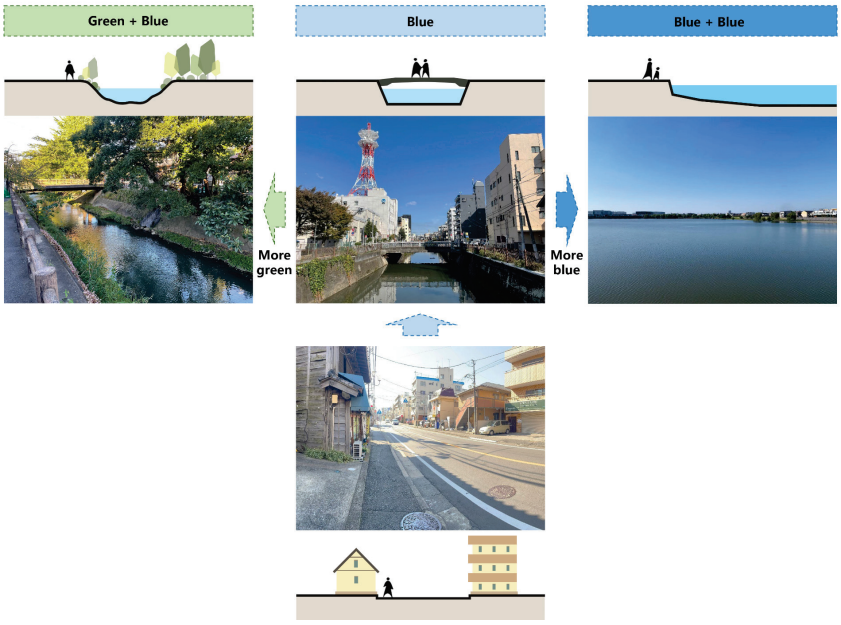



**Figure 9.** Natural health dose reflecting the complementary effect of blue and green elements.

In summary, as a response to previous research [15,32], the current field study findings suggest that the mental health benefits of different freshwater blue spaces may vary depending on the different environmental content (natural element dose) in different environments.

### *4.4. Implications*

The research implications are obvious. First, the results of this experiment may provide foundational evidence for building healthy cities. The "Blue Gym" program, which has been emphasized in several countries, aims to connect people to blue spaces and thus improve psychological health and social well-being [58]. Thus, planners and city managers can determine the areas of residential and urban "blue recreation areas" based on the blue resources (water bodies) available in the city. According to Dzhambov et al. (2018), perceived blue spaces are associated with higher physical activity [13]. In these areas, residents can interact with nature through proximity to water bodies and engage in sports and recreational activities (walking, running, dog walking, socializing). Additionally, viewing natural elements can be a restorative experience [59], and similar to Elsadek et al.'s (2020) study [60], residents can view nearby water bodies through windows for relaxation and psychological recovery. One suggestion involves targeting specific populations (experiencing high stress or low mental health) with appropriate interventions to encourage greater exposure to these blue spaces, such as by increasing aquatic features in buildings and organizing tours of watery environments [17].

Second, the management and design of different blue spaces in a city can also have benefits. For example, if conditions permit, it is desirable to increase the vegetation cover of artificial waterways in a city by adding aquatic plants and vegetation at the water's edge. Additionally, unlike green spaces, expanding water bodies is more difficult owing to high costs, so it is more feasible to develop various blue spaces in a city (e.g., daylighting buried waterways or adding artificial lakes and ponds [61]). Furthermore, landscape architects should provide adequate facilities to use these UBSs, such as benches to support viewing behavior and a "Blueway" for walking (corresponding to the greenway). Finally, maintaining the quality of water and the UBS is necessary, and although this study did not measure relevant data, previous research has shown that low-quality urban waterways (dirty water, odors, floating trash) can reduce therapeutic experiences [26].

Finally, in terms of theoretical contributions, there is less direct health evidence involving blue spaces (e.g., [54]). This study investigated the psychological recovery effects of short visits (15 min of viewing, 15 min of walking) in three different UBS settings through a field experiment, and our current results add to this research gap. Moreover, this experimental design refers to other green space studies [30,35] and obtains high scale reliability, which suggests that this empirical research process can be extended to other potentially restorative spaces, such as gray space [62] and yellow space [63]. Furthermore, the proposed "natural health dose" may raise an interesting discussion about whether there are other restorative elements in the urban environment other than green and blue elements. For example, some studies have found that cultural [64] or artificial elements [65] can also trigger restoration, yet such restoration may need to be achieved through design methods or a degree of coherence with the environment. Therefore, it is recommended to refer to the subjective perception measurement approach in this study to discover the level of various types of restorative elements in different care environments.

### *4.5. Limitations*

It is imperative to acknowledge that this study has some limitations that should be considered in future studies. First, we selected only freshwater blue spaces, excluding urban coastal and seaside environments where the restorative experience may differ from other UBSs. Second, although we speculate that the effect of blue space on physiological health is limited, it is worthwhile to conduct more experiments to verify this hypothesis. Third, seasonal-specific investigations are beneficial, such as that by Bielinis et al. (2018) [47], who found that forest viewing in winter led to psychological relaxation. Along the same lines,

future studies could consider exploring the health-improving effects provided by viewing a frozen lake, as well as the benefits of physical activity in blue spaces in winter. Fourth, exposure time affects the level of psychological recovery [30], so longer walks (30 min or more) and viewing may yield different findings. Fifth, because of the limitations of the sample size, gender, age, and occupational differences were not compared, and future studies could investigate the effects of these different variables on restoration. Sixth, the sample in this study was a healthy population without mental illness, so experimental samples such as high stress, depression, and other mental illnesses are meaningful for urban public health. Seventh, owing to cost and time constraints, only three common types of blue spaces in urban environments were investigated in this study, and investigations of additional types of UBS (e.g., stream, coastal, harbor) are encouraged to complement the results of this manuscript. Eighth, outcomes such as clinical/administrative or sensor data could be used to reflect the psychological restoration in more empirical studies. Finally, the concept of "natural health dose" is proposed. However, owing to space limitations, we did not discuss it in depth, and future studies could quantify the value of "dose" by using visual indices to discuss the complementary effects of green and blue.

## 5. Conclusions

Even though water covers more than two-thirds of the Earth, systematic investigations into blue spaces remain neglected. Different blue spaces in cities have been identified as important contributors to urban public health, but empirical data on this issue is lacking [10], and our current results add to this research gap. Overall, the present study investigated the psychological recovery effects of short visits (15 min of viewing, 15 min of walking) in three different UBS settings through a field experiment. The results confirmed that:

(1) all three UBSs increased vitality, feelings of restoration, positive emotions, and decreased negative emotions, which suggest that the restorative benefits of UBSs are similar to those of other green environments;
(2) the mental restoration effects between walking and viewing among three UBSs showed no significant differences;
(3) of the three UBSs, urban rivers and urban lakes were the most restorative, while urban canals were less so;
(4) the health experiences of different UBSs in urban settings can show differences depending on the natural components and their levels in the environment (blue, blue + green, blue + blue).

The current findings highlight the health value of the different types of blue spaces in cities that structure the blue health network in the urban environment. The results can provide insights for city managers, planners, and landscape architects to better develop appropriate uses and interventions.

**Author Contributions:** Conceptualization, S.L. and J.X.; methodology, S.L. and J.X.; software, S.L.; validation, S.L. and J.X.; formal analysis, S.L. and J.X.; investigation, S.L., J.X., H.W., Q.W. and J.C.; resources, S.L. and Z.Y.; data curation, S.L.; writing—original draft preparation, S.L. and J.X.; writing—review and editing, S.L., J.X., H.W., Q.W., Z.Y. and J.C.; visualization, S.L.; supervision, J.X. and K.F.; project administration, K.F.; funding acquisition, S.L., J.X. and K.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** We would like to thank the Japan Science and Technology Agency for funding this research [grant number JPMJSP2109].

**Data Availability Statement:** Data available on request due to restrictions (e.g., privacy or ethical).

**Acknowledgments:** We would like to thank all experimental participants for their precious time in this study. Moreover, we thank the reviewers and editors for their valuable time in reviewing this manuscript. Additionally, we sincerely thank Takahide Kagawa and Xi Shu for their help in the experimental design of this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Differential results for gender on each psychological indicator at the four sites before the intervention (ANOVA).

| Place | Psychological Indicators | Levene Statistic (Sig.) | Sum of Squares | F | Sig. |
|---|---|---|---|---|---|
| UR (N = 41) | SVS | 0.471 (0.497) | 0.032 | 0.029 | 0.867 |
| | ROS | 0.474 (0.495) | 0.026 | 0.026 | 0.873 |
| | PANAS POS | 0.028 (0.867) | 0.199 | 0.316 | 0.577 |
| | PANAS NEG | 0.177 (0.676) | 0.230 | 0.277 | 0.602 |
| UC (N = 41) | SVS | 0.680 (0.415) | 1.257 | 1.222 | 0.276 |
| | ROS | 1.249 (0.271) | 0.115 | 0.135 | 0.715 |
| | PANAS POS | 0.524 (0.473) | 0.431 | 0.438 | 0.512 |
| | PANAS NEG | 0.277 (0.602) | 0.000 | 0.000 | 0.999 |
| UL (N = 41) | SVS | 0.488 (0.489) | 2.638 | 3.933 | 0.054 |
| | ROS | 0.554 (0.461) | 1.176 | 1.227 | 0.275 |
| | PANAS POS | 0.656 (0.423) | 2.638 | 3.933 | 0.054 |
| | PANAS NEG | 0.056 (0.814) | 0.024 | 0.019 | 0.892 |
| CG (N = 41) | SVS | 0.085 (0.772) | 0.703 | 0.613 | 0.438 |
| | ROS | 0.114 (0.738) | 0.441 | 0.519 | 0.476 |
| | PANAS POS | 0.118 (0.733) | 0.472 | 0.534 | 0.469 |
| | PANAS NEG | 0.024 (0.879) | 0.238 | 0.284 | 0.597 |

Note. UR, Urban River, UC, Urban Canal, UL, Urban Lake, CG, Control Group.

**Table A2.** Correlation (Pearson) matrix for four psychological indicators.

| Place | Correlation | | Before the Experiment (T1) | | | | After Viewing (T2) | | After Walking (T3) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SVS | ROS | POS | NEG | SVS | ROS | SVS | ROS | POS | NEG |
| UR (N = 41) | Before the experiment (T1) | SVS | 1 | 0.69 | 0.84 | −0.35 | 0.73 | 0.55 | 0.66 | 0.59 | 0.54 | −0.38 |
| | | ROS | | 1 | 0.73 | −0.46 | 0.63 | 0.54 | 0.52 | 0.53 | 0.43 | −0.39 |
| | | POS | | | 1 | −0.32 | 0.71 | 0.59 | 0.70 | 0.59 | 0.63 | −0.42 |
| | | NEG | | | | 1 | −0.34 | −0.43 | −0.17 | −0.24 | 0.13 | 0.41 |
| | After viewing (T2) | SVS | | | | | 1 | 0.78 | 0.79 | 0.65 | 0.63 | −0.48 |
| | | ROS | | | | | | 1 | 0.71 | 0.82 | 0.71 | −0.65 |
| | After walking (T3) | SVS | | | | | | | 1 | 0.81 | 0.81 | −0.53 |
| | | ROS | | | | | | | | 1 | 0.87 | −0.71 |
| | | POS | | | | | | | | | 1 | −0.65 |
| | | NEG | | | | | | | | | | 1 |
| UC (N = 41) | Before the experiment (T1) | SVS | 1 | 0.76 | 0.77 | −0.34 | 0.54 | 0.28 | 0.37 | 0.39 | 0.39 | −0.29 |
| | | ROS | | 1 | 0.75 | −0.43 | 0.51 | 0.42 | 0.31 | 0.47 | 0.37 | −0.34 |
| | | POS | | | 1 | −0.34 | 0.59 | 0.50 | 0.38 | 0.53 | 0.47 | −0.26 |
| | | NEG | | | | 1 | 0.18 | 0.05 | 0.20 | 0.03 | 0.13 | 0.60 |
| | After viewing (T2) | SVS | | | | | 1 | 0.75 | 0.79 | 0.69 | 0.70 | −0.17 |
| | | ROS | | | | | | 1 | 0.71 | 0.80 | 0.73 | −0.42 |
| | After walking (T3) | SVS | | | | | | | 1 | 0.81 | 0.81 | −0.31 |
| | | ROS | | | | | | | | 1 | 0.88 | −0.47 |
| | | POS | | | | | | | | | 1 | −0.33 |
| | | NEG | | | | | | | | | | 1 |

**Table A2.** *Cont.*

| Place | Correlation | | Before the Experiment (T1) | | | | After Viewing (T2) | | After Walking (T3) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **SVS** | **ROS** | **POS** | **NEG** | **SVS** | **ROS** | **SVS** | **ROS** | **POS** | **NEG** |
| UL (N = 41) | Before the experiment (T1) | SVS | 1 | 0.59 | 0.72 | −0.22 | 0.71 | 0.63 | 0.69 | 0.52 | 0.55 | −0.50 |
| | | ROS | | 1 | 0.78 | −0.45 | 0.42 | 0.42 | 0.37 | 0.39 | 0.26 | −0.41 |
| | | POS | | | 1 | −0.34 | 0.50 | 0.51 | 0.53 | 0.46 | 0.51 | −0.40 |
| | | NEG | | | | 1 | −0.10 | −0.13 | 0.03 | 0.06 | 0.19 | 0.48 |
| | After viewing (T2) | SVS | | | | | 1 | 0.71 | 0.73 | 0.67 | 0.70 | −0.46 |
| | | ROS | | | | | | 1 | 0.71 | 0.73 | 0.69 | −0.41 |
| | After walking (T3) | SVS | | | | | | | 1 | 0.77 | 0.83 | −0.51 |
| | | ROS | | | | | | | | 1 | 0.89 | −0.54 |
| | | POS | | | | | | | | | 1 | −0.42 |
| | | NEG | | | | | | | | | | 1 |
| CG (N = 41) | Before the experiment (T1) | SVS | 1 | 0.77 | 0.78 | −0.31 | 0.73 | 0.46 | 0.70 | 0.35 | 0.49 | −0.19 |
| | | ROS | | 1 | 0.77 | −0.51 | 0.78 | 0.59 | 0.68 | 0.45 | 0.45 | −0.40 |
| | | POS | | | 1 | −0.47 | 0.66 | 0.51 | 0.70 | 0.41 | 0.53 | −0.33 |
| | | NEG | | | | 1 | −0.34 | −0.45 | −0.27 | −0.43 | −0.30 | 0.71 |
| | After viewing (T2) | SVS | | | | | 1 | 0.61 | 0.72 | 0.53 | 0.62 | −0.34 |
| | | ROS | | | | | | 1 | 0.56 | 0.70 | 0.57 | −0.58 |
| | After walking (T3) | SVS | | | | | | | 1 | 0.67 | 0.77 | −0.37 |
| | | ROS | | | | | | | | 1 | 0.80 | −0.63 |
| | | POS | | | | | | | | | 1 | −0.44 |
| | | NEG | | | | | | | | | | 1 |

Note. UR, Urban River, UC, Urban Canal, UL, Urban Lake, CG, Control Group. The numbers in the table represent the correlation coefficients. Green cells indicate $p < 0.05$ and blue cells indicate $p < 0.01$ while the cells without color indicate insignificance.

## References


1. Song, C.; Ikei, H.; Park, B.J.; Lee, J.; Kagawa, T.; Miyazaki, Y. Association between the psychological effects of viewing forest landscapes and trait anxiety level. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5479. [CrossRef] [PubMed]
2. Tanaka, A.; Takano, T.; Nakamura, K.; Takeuchi, S. Health levels influenced by urban residential conditions in a megacity—Tokyo. *Urban Stud.* **1996**, *33*, 879–894. [CrossRef]
3. Peen, J.; Schoevers, R.A.; Beekman, A.T.; Dekker, J. The current status of urban-rural differences in psy-chiatric disorders. *Acta Psychiatr. Scand.* **2010**, *121*, 84–93. [CrossRef]
4. McKenzie, K.; Murray, A.; Booth, T. Do urban environments increase the risk of anxiety, depression and psychosis? An epidemiological study. *J. Affect. Disord.* **2013**, *150*, 1019–1024. [CrossRef] [PubMed]
5. Elsadek, M.; Liu, B.; Lian, Z.; Xie, J. The influence of urban roadside trees and their physical environment on stress relief measures: A field experiment in Shanghai. *Urban For. Urban Green.* **2019**, *42*, 51–60. [CrossRef]
6. McDougall, C.W.; Quilliam, R.S.; Hanley, N.; Oliver, D.M. Freshwater blue space and population health: An emerging research agenda. *Sci. Total Environ.* **2020**, *737*, 140196. [CrossRef] [PubMed]
7. Subiza-Pérez, M.; Hauru, K.; Korpela, K.; Haapala, A.; Lehvävirta, S. Perceived Environmental Aesthetic Qualities Scale (PEAQS)–A self-report tool for the evaluation of green-blue spaces. *Urban For. Urban Green.* **2019**, *43*, 126383. [CrossRef]
8. Völker, S.; Heiler, A.; Pollmann, T.; Claßen, T.; Hornberg, C.; Kistemann, T. Do perceived walking distance to and use of urban blue spaces affect self-reported physical and mental health? *Urban For. Urban Green.* **2018**, *29*, 1–9. [CrossRef]
9. Foley, R.; Kistemann, T. Blue space geographies: Enabling health in place. *Health Place* **2015**, *35*, 157–165. [CrossRef]
10. Völker, S.; Matros, J.; Claßen, T. Determining urban open spaces for health-related appropriations: A quali-tative analysis on the significance of blue space. *Environ. Earth Sci.* **2016**, *75*, 1–18. [CrossRef]
11. Van den Bogerd, N.; Elliott, L.R.; White, M.P.; Mishra, H.S.; Bell, S.; Porter, M.; Sydenham, Z.; Garrett, J.K.; Fleming, L.E. Urban blue space renovation and local resident and visitor well-being: A case study from Plymouth, UK. *Landsc. Urban Plan.* **2021**, *215*, 104232. [CrossRef]
12. Pasanen, T.P.; White, M.P.; Wheeler, B.W.; Garrett, J.K.; Elliott, L.R. Neighbourhood blue space, health and wellbeing: The mediating role of different types of physical activity. *Environ. Int.* **2019**, *131*, 105016. [CrossRef] [PubMed]
13. Dzhambov, A.M.; Markevych, I.; Hartig, T.; Tilov, B.; Arabadzhiev, Z.; Stoyanov, D.; Gatseva, P.; Dimitrova, D.D. Multiple pathways link urban green-and bluespace to mental health in young adults. *Environ. Res.* **2018**, *166*, 223–233. [CrossRef] [PubMed]
14. Elliott, L.R.; White, M.P.; Grellier, J.; Garrett, J.K.; Cirach, M.; Wheeler, B.W.; Bratman, G.N.; van den Bosch, M.A.; Ojala, A.; Roiko, A.; et al. Research Note: Res-idential distance and recreational visits to coastal and inland blue spaces in eighteen countries. *Landsc. Urban Plan.* **2020**, *198*, 103800. [CrossRef]

15. Poulsen, M.N.; Nordberg, C.M.; Fiedler, A.; DeWalle, J.; Mercer, D.; Schwartz, B.S. Factors associated with visiting freshwater blue space: The role of restoration and relations with mental health and well-being. *Landsc. Urban Plan.* **2022**, *217*, 104282. [CrossRef]
16. Luo, S.; Xie, J.; Furuya, K. Assessing the Preference and Restorative Potential of Urban Park Blue Space. *Land* **2021**, *10*, 1233. [CrossRef]
17. White, M.; Smith, A.; Humphryes, K.; Pahl, S.; Snelling, D.; Depledge, M. Blue space: The importance of water for preference, affect, and restorativeness ratings of natural and built scenes. *J. Environ. Psychol.* **2010**, *30*, 482–493. [CrossRef]
18. Bulut, Z.; Yilmaz, H. Determination of waterscape beauties through visual quality assessment method. *Environ. Monit. Assess.* **2009**, *154*, 459–468. [CrossRef]
19. Nasar, J.L.; Li, M. Landscape mirror: The attractiveness of reflecting water. *Landsc. Urban Plan.* **2004**, *66*, 233–238. [CrossRef]
20. Herzog, T.R. A cognitive analysis of preference for waterscapes. *J. Environ. Psychol.* **1985**, *5*, 225–241. [CrossRef]
21. Hermanski, A.; McClelland, J.; Pearce-Walker, J.; Ruiz, J.; Verhougstraete, M. The effects of blue spaces on mental health and associated biomarkers. *Int. J. Ment. Health* **2022**, *51*, 203–217. [CrossRef]
22. Engemann, K.; Svenning, J.C.; Arge, L.; Brandt, J.; Erikstrup, C.; Geels, C.; Hertel, O.; Mortensen, P.B.; Plana-Ripoll, O.; Tsirogiannis, C.; et al. Associations be-tween growing up in natural environments and subsequent psychiatric disorders in Denmark. *Environ. Res.* **2020**, *188*, 109788. [CrossRef] [PubMed]
23. Georgiou, M.; Tieges, Z.; Morison, G.; Smith, N.; Chastin, S. A population-based retrospective study of the modifying effect of urban blue space on the impact of socioeconomic deprivation on mental health, 2009–2018. *Sci. Rep.* **2022**, *12*, 13040. [CrossRef] [PubMed]
24. Stieger, S.; Aichinger, I.; Swami, V. The impact of nature exposure on body image and happiness: An expe-rience sampling study. *Int. J. Environ. Health Res.* **2022**, *32*, 870–884. [CrossRef]
25. Reeves, J.P.; Knight, A.T.; Strong, E.A.; Heng, V.; Neale, C.; Cromie, R.; Vercammen, A. The application of wearable technology to quantify health and wellbeing co-benefits from urban wetlands. *Front. Psychol.* **2019**, *10*, 1840. [CrossRef] [PubMed]
26. Pitt, H. Muddying the waters: What urban waterways reveal about bluespaces and wellbeing. *Geoforum* **2018**, *92*, 161–170. [CrossRef]
27. Pitt, H. What prevents people accessing urban bluespaces? A qualitative study. *Urban For. Urban Green.* **2019**, *39*, 89–97. [CrossRef]
28. Korpela, K.M.; Ylén, M.; Tyrväinen, L.; Silvennoinen, H. Favorite green, waterside and urban environments, restorative experiences and perceived health in Finland. *Health Promot. Int.* **2010**, *25*, 200–209. [CrossRef]
29. Carrus, G.; Lafortezza, R.; Colangelo, G.; Dentamaro, I.; Scopelliti, M.; Sanesi, G. Relations between naturalness and perceived restorativeness of different urban green spaces. *Psyecology* **2013**, *4*, 227–244. [CrossRef]
30. Tyrväinen, L.; Ojala, A.; Korpela, K.; Lanki, T.; Tsunetsugu, Y.; Kagawa, T. The influence of urban green environments on stress relief measures: A field experiment. *J. Environ. Psychol.* **2014**, *38*, 1–9. [CrossRef]
31. Lin, W.; Chen, Q.; Jiang, M.; Zhang, X.; Liu, Z.; Tao, J.; Wu, L.; Xu, S.; Kang, Y.; Zeng, Q. The effect of green space behaviour and per capita area in small urban green spaces on psychophysiological responses. *Landsc. Urban Plan.* **2019**, *192*, 103637. [CrossRef]
32. McDougall, C.W.; Hanley, N.; Quilliam, R.S.; Oliver, D.M. Blue space exposure, health and well-being: Does freshwater type matter? *Landsc. Urban Plan.* **2022**, *224*, 104446. [CrossRef]
33. Song, C.; Ikei, H.; Park, B.J.; Lee, J.; Kagawa, T.; Miyazaki, Y. Psychological benefits of walking through forest areas. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2804. [CrossRef] [PubMed]
34. Song, C.; Ikei, H.; Kagawa, T.; Miyazaki, Y. Physiological and psychological effects of viewing forests on young women. *Forests* **2019**, *10*, 635. [CrossRef]
35. Simkin, J.; Ojala, A.; Tyrväinen, L. Restorative effects of mature and young commercial forests, pristine old-growth forest and urban recreation forest-A field experiment. *Urban For. Urban Green.* **2020**, *48*, 126567. [CrossRef]
36. Korpela, K.M.; Ylén, M.; Tyrväinen, L.; Silvennoinen, H. Determinants of restorative experiences in everyday favorite places. *Health Place* **2008**, *14*, 636–652. [CrossRef]
37. Ryan, R.M.; Frederick, C. On energy, personality, and health: Subjective vitality as a dynamic reflection of well-being. *J. Personal.* **1997**, *65*, 529–565. [CrossRef] [PubMed]
38. Watson, D.; Clark, L.A.; Tellegen, A. Development and validation of brief measures of positive and negative affect: The PANAS scales. *J. Personal. Soc. Psychol.* **1988**, *54*, 1063. [CrossRef]
39. Kaplan, S. Meditation, restoration, and the management of mental fatigue. *Environ. Behav.* **2001**, *33*, 480–506. [CrossRef]
40. Ulrich, R.S.; Simons, R.F.; Losito, B.D.; Fiorito, E.; Miles, M.A.; Zelson, M. Stress recovery during exposure to natural and urban environments. *J. Environ. Psychol.* **1991**, *11*, 201–230. [CrossRef]
41. Jiang, B.; He, J.; Chen, J.; Larsen, L.; Wang, H. Perceived green at speed: A simulated driving experiment raises new questions for attention restoration theory and stress reduction theory. *Environ. Behav.* **2021**, *53*, 296–335. [CrossRef]
42. Shu, X.; Mesimäki, M.; Kotze, D.J.; Wales, M.; Xie, L.; Benicke, R.; Lehvävirta, S. Needs and expectations of German and Chinese children for livable urban green spaces revealed by the method of empathy-based stories. *Urban For. Urban Green.* **2022**, *68*, 127476. [CrossRef]
43. Hussain, J.; Wang, X.; Sousa, L.; Ali, R.; Rittmann, B.E.; Liao, W. Using non-metric multi-dimensional scaling analysis and multi-objective optimization to evaluate green algae for production of proteins, carbohydrates, lipids, and simultaneously fix carbon dioxide. *Biomass Bioenergy* **2020**, *141*, 105711. [CrossRef]

44. Mielke, P.W., Jr.; Berry, K.J.; Johnson, E.S. Multi-response permutation procedures for a priori classifications. *Commun. Stat.-Theory Methods* **1976**, *5*, 1409–1424. [CrossRef]
45. Oksanen, J.; Kindt, R.; Legendre, P.; O'Hara, B.; Stevens, M.H.H.; Oksanen, M.J.; Suggests, M.A.S.S. The vegan package. *Community Ecol. Package* **2007**, *10*, 719.
46. Faul, F.; Erdfelder, E.; Lang, A.G.; Buchner, A. G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* **2007**, *39*, 175–191. [CrossRef] [PubMed]
47. Rouse, P.C.; Van Zanten, J.J.V.; Ntoumanis, N.; Metsios, G.S.; Yu, C.A.; Kitas, G.D.; Duda, J.L. Measuring the positive psychological well-being of people with rheumatoid arthritis: A cross-sectional validation of the subjective vitality scale. *Arthritis Res. Ther.* **2015**, *17*, 1–7. [CrossRef] [PubMed]
48. Bielinis, E.; Takayama, N.; Boiko, S.; Omelan, A.; Bielinis, L. The effect of winter forest bathing on psychological relaxation of young Polish adults. *Urban For. Urban Green.* **2018**, *29*, 276–283. [CrossRef]
49. Tugade, M.M.; Fredrickson, B.L.; Feldman Barrett, L. Psychological resilience and positive emotional gran-ularity: Examining the benefits of positive emotions on coping and health. *J. Personal.* **2004**, *72*, 1161–1190. [CrossRef] [PubMed]
50. Mattila, O.; Korhonen, A.; Pöyry, E.; Hauru, K.; Holopainen, J.; Parvinen, P. Restoration in a virtual reality forest environment. *Comput. Hum. Behav.* **2020**, *107*, 106295. [CrossRef]
51. Gidlow, C.J.; Jones, M.V.; Hurst, G.; Masterson, D.; Clark-Carter, D.; Tarvainen, M.P.; Smith, G.; Nieuwenhuijsen, M. Where to put your best foot forward: Psycho-physiological responses to walking in natural and urban environments. *J. Environ. Psychol.* **2016**, *45*, 22–29. [CrossRef]
52. Luo, L.; Yu, P.; Jiang, B. Differentiating mental health promotion effects of various bluespaces: An electro-encephalography study. *J. Environ. Psychol.* **2023**, *88*, 102010. [CrossRef]
53. Gelman, R.; Berg, M.; Ilan, Y. A subject-tailored variability-based platform for overcoming the plateau effect in sports training: A narrative review. *Int. J. Environ. Res. Public Health* **2022**, *19*, 1722. [CrossRef] [PubMed]
54. Vert, C.; Gascon, M.; Ranzani, O.; Márquez, S.; Triguero-Mas, M.; Carrasco-Turigas, G.; Arjona, L.; Koch, S.; Llopis, M.; Donaire-Gonzalez, D.; et al. Physical and mental health effects of repeated short walks in a blue space environment: A randomised crossover study. *Environ. Res.* **2020**, *188*, 109812. [CrossRef]
55. Pratiwi, P.I.; Xiang, Q.; Furuya, K. Physiological and psychological effects of walking in urban parks and its imagery in different seasons in middle-aged and older adults: Evidence from matsudo city, Japan. *Sustainability* **2020**, *12*, 4003. [CrossRef]
56. Jiang, B.; Chang, C.Y.; Sullivan, W.C. A dose of nature: Tree cover, stress reduction, and gender differences. *Landsc. Urban Plan.* **2014**, *132*, 26–36. [CrossRef]
57. Wilson, E.O. Biophilia and the conservation ethic. In *The Biophilia Hypothesis*; Kellert, S., Wilson, E.O., Eds.; Island Press: Washington, DC, USA, 1993.
58. Depledge, M.H.; Bird, W.J. The Blue Gym: Health and wellbeing from our coasts. *Mar. Pollut. Bull.* **2009**, *58*, 947–948. [CrossRef] [PubMed]
59. Tennessen, C.M.; Cimprich, B. Views to nature: Effects on attention. *J. Environ. Psychol.* **1995**, *15*, 77–85. [CrossRef]
60. Elsadek, M.; Liu, B.; Xie, J. Window view and relaxation: Viewing green space from a high-rise estate improves urban dwellers' wellbeing. *Urban For. Urban Green.* **2020**, *55*, 126846. [CrossRef]
61. Haeffner, M.; Jackson-Smith, D.; Buchert, M.; Risley, J. Accessing blue spaces: Social and geographic factors structuring familiarity with, use of, and appreciation of urban waterways. *Landsc. Urban Plan.* **2017**, *167*, 136–146. [CrossRef]
62. Subiza-Perez, M.; Vozmediano, L.; San Juan, C. Welcome to your plaza: Assessing the restorative potential of urban squares through survey and objective evaluation methods. *Cities* **2020**, *100*, 102461. [CrossRef]
63. Wang, K.; Cui, Q.; Xu, H. Desert as therapeutic space: Cultural interpretation of embodied experience in sand therapy in Xinjiang, China. *Health Place* **2018**, *53*, 173–181. [CrossRef] [PubMed]
64. Gallou, E.; Uzzell, D.; Sofaer, J. Perceived place qualities, restorative effects and self-reported wellbeing benefits of visits to heritage sites: Empirical evidence from a visitor survey in England. *Wellbeing Space Soc.* **2022**, *3*, 100106. [CrossRef]
65. Luo, S.; Shi, J.; Lu, T.; Furuya, K. Sit down and rest: Use of virtual reality to evaluate preferences and mental restoration in urban park pavilions. *Landsc. Urban Plan.* **2022**, *220*, 104336. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

*Article*

# Using Social Media and Multi-Source Geospatial Data for Quantifying and Understanding Visitor's Preferences in Rural Forest Scenes: A Case Study from Nanjing

**Chongxiao Wang, Jiahui Zou, Xinyuan Fang, Shuolei Chen and Hao Wang ***

School of Landscape Architecture, Nanjing Forestry University, Nanjing 210037, China; chongxiao@njfu.edu.cn (C.W.); zoujiahuiqqq@gmail.com (J.Z.); fxy1803@gmail.com (X.F.); shuoleichen@njfu.edu.cn (S.C.)

* Correspondence: wanghao2022@njfu.edu.cn; Tel.: +86-138-0516-9757

**Abstract:** Rapid urbanization has made urban forest scenes scarce resources, leading to a surge in the demand for high-quality rural forest scenes as alternative outdoor recreation spaces. Previous studies mainly applied survey methods, focusing on visitors' feedback for different types of scenes from the perspective of visual quality evaluation. Nevertheless, the explanations of the relationships between various factors of scenes and visitors' preferences are relatively superficial. This study sought to explore the distribution and characteristics of preferred rural forest scenes based on visitor reviews from social media, and using Geodetector, a geospatial statistics tool, to quantitatively analyzed the reasons for visitors' preferences in terms of factors obtained from multi-source geospatial data. The findings are that (1) visitors are already satisfied with the natural environment but expect scenes that reflect the culture of tea; (2) spatial factor has a more robust interpretation of visitors' preference, and although the Normalized Difference Vegetation Index (NDVI) and non-consumption indicators barely explain visitors' preference solely when each of them is combined with other indicators, they can produce non-linear enhancement effects. Consequently, this study synthesizes visitors' feedback and factors in rural forest scenes to understand visitors' preferences, thus providing insights into human-centered planning.

**Keywords:** rural forest scenes; visitors' preference; social media data; multi-source geospatial data; Geodetector; machine learning

**Citation:** Wang, C.; Zou, J.; Fang, X.; Chen, S.; Wang, H. Using Social Media and Multi-Source Geospatial Data for Quantifying and Understanding Visitor's Preferences in Rural Forest Scenes: A Case Study from Nanjing. *Forests* **2023**, *14*, 1932. https://doi.org/10.3390/f14101932

Academic Editors: Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Baojie He and Shi Cheng

Received: 26 August 2023
Revised: 5 September 2023
Accepted: 18 September 2023
Published: 22 September 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Rapid urbanization along with more intensive urban buildings and crowded spaces has resulted in a decline in environmental quality of urban areas [1]. Urban forest scenes refer to the scenes with enough green environment in urban built areas, including plazas, lawns, garden paths, ponds, rockeries, etc. [2]. High-quality urban forest scenes are becoming scarce sources for people who live in urban areas. A trend exists that citizens are interested in finding alternative outdoor spaces for leisure and recreational activities [3]. As a type of semi-artificial natural environment in villages, rural forest scenes are one type of rural public space, referring to the outdoor public spaces based on the countryside's natural environment and cultural resources [4]. Villages with satisfactory rural forest scenes are becoming popular destinations for urban populations, which has promoted local tourism development [5].

Tourism-oriented planning methods take tourism as an engine for rural economic and social development and aim to attract visitors [6]. When observing the villages applying these methods, the rural areas' socio-economic morphology and spatial pattern are dramatically restructured [7]. Visitors' preferences, referring to the expression of a visitor's favor, can reflect the willingness of visitors to choose a scene and their degree of satisfaction with it. Therefore, visitors' preferences are closely related to the attractiveness of a village,

and insights from visitors' preferences help to guide the construction and capitalize on the positive effects of tourism on village development. Contrary to the ambition of revival, the allocation of village factors may fail to meet the factual demand, causing unreasonable utilization of the precious and limited village resources. Previous research revealed the potential value visitors could bring to villages, but visitors' preference for rural forest scenes was not thoroughly analyzed [5].

Currently, most studies on visitors' preferences were conducted in built-up urban areas and focused on urban forest scenes. Arne Arnberger and Renate Eder [8] developed a conceptual framework and four choice sets, each consisting of four image- and text-based green-space scenarios (stated choice survey) was shown to each respondent to investigate the preferences for site characteristics green-space urban visitors have when they are seeking stress relief compared to their general green-space preferences. In terms of evaluation indicators, previous studies focused on natural factors. For instance, Canliu Li et al. [9] conducted scenic beauty estimation (SBE) of the landscape factors in 29 winter plant communities to evaluate the aesthetic characteristics of the plant landscape using photographs. Findings in urban forest scenes were that the vegetation-related and water-related evaluation indicators turn out to be the major factors influencing visitors' preferences [10].

In conclusion, outdoor recreation planners, land use planners, and researchers often turn to on-site surveys as the primary methods [11], including face-to-face methods in scenes, such as semi-structured interviews [12] and open-ended interviews [13], or photography as a proxy of the natural environment to indirectly assess visitors' responses to urban forest scenes [14–16]. However, a low response rate is a common problem for survey-based studies, mainly because respondents do not have enough time or are not interested in participating in the study [8,17], which is one of the reasons for the high research costs.

In the context of the new data environment, social media data provide researchers access to a large amount of visitor-related data compared with traditional surveys. All the content from social media, including travel-related comments [18] and on-site photos, were voluntarily uploaded by visitors, reducing the cost that researchers needed to invest in collecting data [19]. Analyzing the tourism comments obtained from Mafengwo, one of the influential tourism social networking sites, Qiusheng Li et al. [20] effectively analyzed tourists' regional tendencies and emotional changes. However, given that over 70% of the original datasets might be noise or non-relevant messages, plenty of data from social media are unstructured, subjective, and exist in massive databases [21]. When studying visitors' preferences, the heterogeneous data from social media lack spatially explicit information and have flaws in spatiotemporal analysis in a fine-scaled village.

Additionally, survey-based studies on urban forest scenes tended to pay attention to visitor's perception or attitudes from the perspective of visual quality evaluation [10]. The visual quality evaluation allows respondents to express their attitudes toward objects based on visual perception, thereby measuring the quality of the object. The visual quality evaluation in preference studies represents the most realistic opinion of humans toward a physical scene, an image, or a video [22]. It remains to be validated whether the conclusions drawn from the urban forest scenes are equally applicable to the rural forest scenes. A previous study highlighted the importance of other endogenous resources as preconditions for the development of tourism [23]. However, other potential factors affecting preference, such as socio-economic and spatial factors, were not given enough attention in rural forest scene studies.

Multi-source geospatial data can be utilized to reveal the detailed characteristics of various factors influencing visitors' preferences. Points of interest (POIs) are locations that, historically, cartographers have added to maps to communicate an interesting or relevant named place, using cartographic symbols and labels. POIs typically include visually and culturally important features and can be used to show the locations of these features [24]. Commonly used in the urban built environment [25,26], POIs are used to perceive the socio-economic environmental characteristics. Street networks collected from the Open

Street Map (OSM) were utilized to explore the spatial configurations and how these spatial configurations affect visitors' behaviors [26–28] using a space syntax analysis tool, which has long been used in architecture [27] and urban design [29]. Unmanned Aerial Vehicle (UAV) is characterized by the superiority of full perspective, high realism [30], and fast and on-demand data acquisition [31], and is applied to capture fine-scaled information about a village [32].

In summary, social media and multi-source geospatial data supplemented detailed information on studying visitors' preferences compared to traditional surveys. Consequently, based on social media and multi-source geospatial data in rural forest scenes, there is a call for comprehensive explanations of visitors' preferences based on fully characterizing visitors' preferences and describing the potential factors affecting visitors' preferences.

According to the previous discussion, for a better understanding of visitor's preference in rural forest scenes, there do exist two gaps to be investigated:

1. Lack of cost-effective methods for acquiring, processing, and analyzing visitor-related data to describe the content of visitors' feedback comprehensively;
2. Lack of in-depth exploration of the effects of various factors in the rural forest scenes on visitors' preferences in addition to natural factors.

This study sought to explore the distribution and characteristics of preferred rural forest scenes based on visitor reviews from social media, and using Geodetector, a geospatial statistics tool, quantitatively analyzing the reasons for visitors' preferences in terms of factors obtained from multi-source geospatial data.

## 2. Materials and Methods

### *2.1. Study Area and Research Framework*

In this study, we took the Huanglongxian Village (Figure 1) in the suburb of Nanjing as the empirical study area to quantify and understand visitors' preferences in rural forest scenes. Located in the community of Pai Fang, the southwest corner of Jiangning District, Huanglongxian Village is 40 km from the central city of Nanjing. It is famous as "Jinling Tea Village" for tea culture and ecological leisure tourism. In the past decade, it has received more than 2 million visitors.

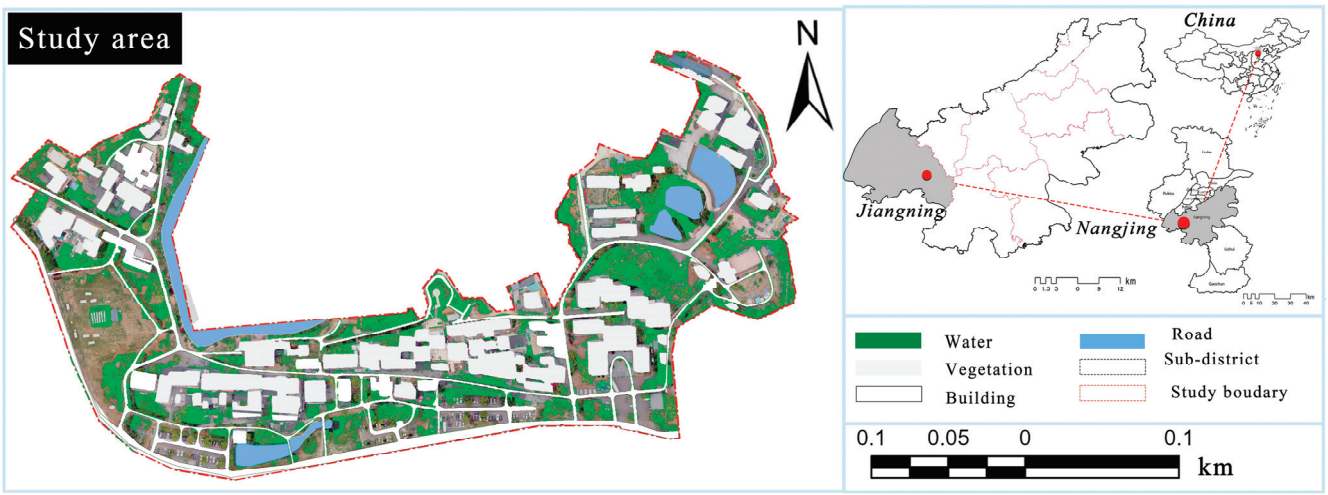



**Figure 1.** The extent of the study area, Huanglongxian, China.

Surrounded by tea mountains and a lake adjacent to it from the north by right, the total area of this Village included in the study is about 9.9 hectares. It is distributed in an overall east–west direction along the north of the arterial highway, which is the area where the main villagers live, and most tourists visit. With a representative tea culture, natural environment, and sufficient visitor data, Huanglongxian Village can be a qualified case to study visitors' preferences.

In response to the gaps mentioned above, this study developed a framework, which is shown in Figure 2. Based on social media and multi-source geospatial data and corresponding analysis strategies, this framework consists of four components: data collection, data preprocessing, quantification and modeling, and understanding establishment. Performing these procedures, this framework aimed to figure out the following questions:

1. Which rural forest scenes do visitors prefer?
2. What are the characteristics of these rural forest scenes preferred by visitors?
3. How are other factors of the rural forest scenes in addition to natural factors distributed?
4. How can factors of rural forest scenes explain visitors' preferences?

To answer these questions, (1) social media data, including comments and photos, were adopted according to detailed data collection and "noise" reduction (data cleaning and screening) criteria to reflect the visitor-preferred rural forest scenes; (2) screened photos were processed using CV technology to reveal the characteristics of the rural forest scenes preferred by visitors, and comments were hierarchically analyzed using NLP models for recognizing the heterogeneousness of visitors' attitudes; (3) the distribution of socio-economic factor, spatial factor and natural factor were extracted from multi-source geospatial data; (4) visitors' preferences and factors of rural forest scenes were modeled using Geodector to explore their potential association.

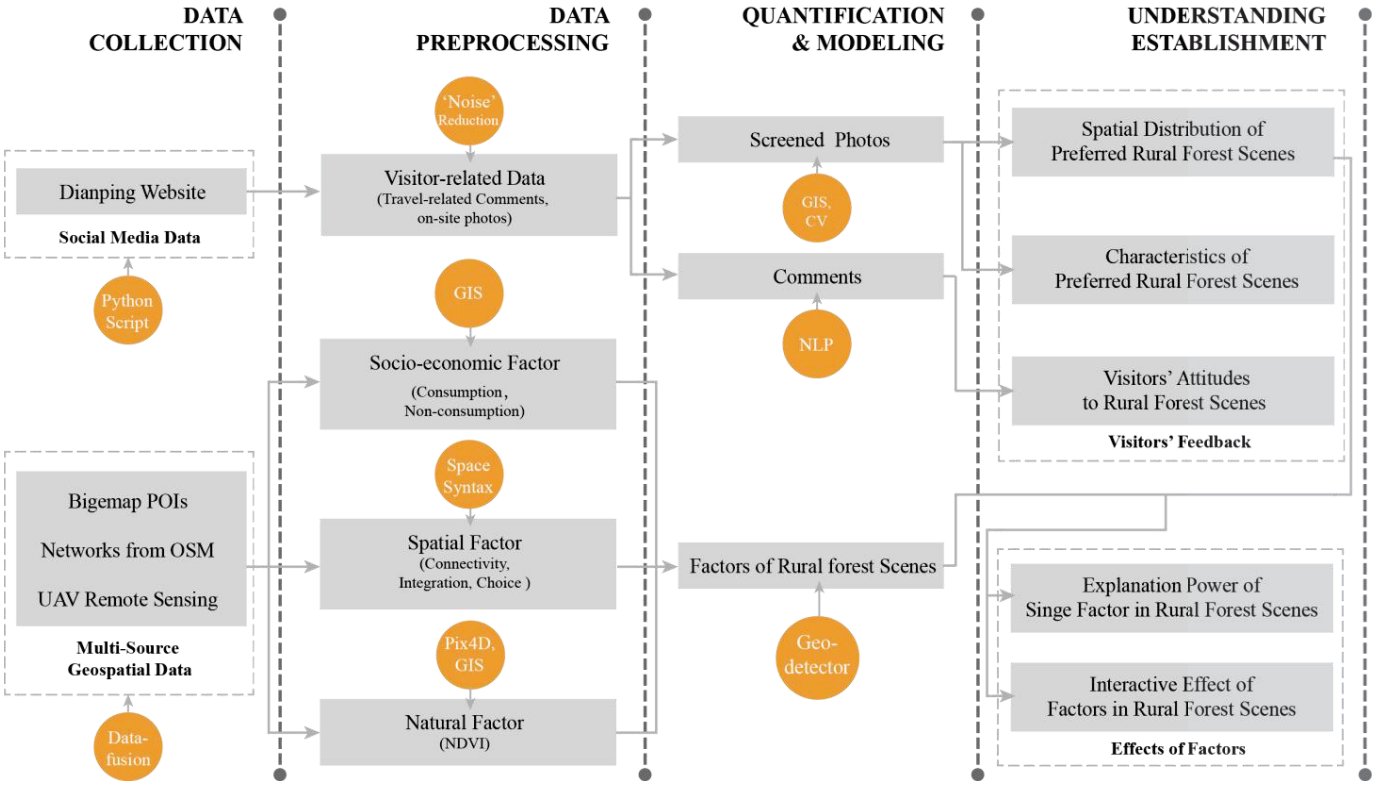



**Figure 2.** The data-fusion framework of this research.

## *2.2. Data Collection and Preprocessing*

### 2.2.1. Acquisition of Social Media Data

In this study, visitors' reviews, one of the most visitor-related social media data, were taken to obtain the targeted information on visitors' behavior [33]. The Dianping website, a reliable social media data source for visitors' activities in green spaces [34], allows visitors to rate attractions and upload text comments attaching photos.

Based on the web crawler technology, we collected photos and comments from web sources by extracting web content from a list of Uniform Resource Locators (URLs) [19,35]. This study identified and scraped web elements with the target information using the Selenium package in Python [19], and all data stored in web elements found by Selenium were saved and cleaned using a regular expression to remove the redundant and noisy records.

#### 2.2.2. Screening of Social Media Data

The photos shared by visitors, to a certain extent, reflect the visitors' preference for the content photographed. For the photo to more clearly reflect the visitor's preference for the rural forest scenes of Huanglongxian Village, these photos need to be screened. If the same visitor uploaded multiple photos reflecting the same scene, only one was retained, and the rest were excluded; if multiple photos were combined in the same image, they were processed separately. The screening criteria are as follows to reduce the data "noise":

1. Photos in which visitors clearly expressed negative comments in their comments were excluded;
2. Photos with single subjects, such as people, plants, animals, food, signs, etc., and those that reflect the indoor scene were excluded;
3. Other photos that are unrelated to the content of the current rural forest scenes or fail to identify the specific geographical location were accurately excluded.

#### 2.2.3. Acquisition of Muti-Source Geospatial Data

For this research, we obtained fine-scaled geospatial data from map service providers, including POIs and street networks, and UAV remote sensing data.

1. Map service provider data: POIs were fetched from Bigemap, a widely used map service provider in China, and street networks were fetched from OSM. All these data were supplemented with on-site observation. After applying the correction algorithm to correct the data to the WGS-84 coordinate system and project it to the World Mercator system, their accuracy could meet the research needs.
2. UAV remote sensing data: The UAV (DJI Mavic Air 2) was conducted at low altitudes (100 m flight height above the ground) with $-90^{\circ}$ of gimbal tilt angle, guaranteeing high spatial resolution [36] and mapping accuracy [37]. The time of the aerial survey was 29 April 2023, and there was sufficient daylight, 20 km/h wind speed at the site, and no electromagnetic interference in the surrounding environment to meet the requirements of UAV remote sensing. The study site was photographed in a "zigzag" pattern, and the overlap between horizontal and vertical pixels of each image was guaranteed to be more than 1/3 so that a Digital Orthophoto Map (DOM) of the village could be obtained using Pix4Dmapper (Version 4.4.12) software.

#### 2.2.4. Factors of Rural Forest Scene Extraction

1. Extraction of socio-economic factors from POIs: For fully utilizing relatively high accuracy positioning and multilevel categories [38] of POIs, all POIs were classified into consumption and non-consumptions (Table 1). Each of these categories of POIs was geo-processed by the KDE in ArcGIS (same as for visualizing visitor preferences), and the results separately reflected the socio-economic factor.
2. Extraction of spatial factors from street networks: Street network data obtained from OSM were amended and supplemented according to the fine-scaled DOM obtained from UAV to fix errors in the OSM, in which the deviating street network was deleted, and the missing street network was added manually. Space syntax tools were applied to extract spatial factors by calculating configurative spatial relationships of street networks [39]. In this study, the segment model of space syntax was chosen to describe the networks quantitatively, and both angular and metric parameters were analyzed, including Connectivity, Integration, and Choice [40] (Table 1).

3. Extraction of natural factors from UVA: The Normalized Difference Vegetation Index (NDVI) (Table 1) quantifies vegetation by measuring the difference between near-infrared light (which vegetation strongly reflects) and red light (which vegetation absorbs) [41], which was selected to represent the natural factor of rural forest scenes Taking advantage of the contrast of the characteristics of two bands from the DOM obtained by UVA, we utilized the Arithmetic function in ArcGIS to get the NDVI of the village. The NDVI equation [42] is as follows:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

where *NIR* is the pixel values from the near-infrared band, and *Red* is the pixel values from the red band.

**Table 1.** The data sources and description of all variables.

| Variables | Data Source | Description | Reference |
|---|---|---|---|
| Explained Variable (Y) | | | |
| Y: Visitor Preference | Dianping | Based on systematic observation, we identified the location of the visitor preference scenes from photos posted by visitors on Dianping.com. These location points were geo-processed by KDE, and the result of data smoothing represented the Visitor Preference. | Yiwei Huang et al. [19] Silverman et al. [43] |
| Explanatory Variables (X) | | | |
| Socio-economic factor | | | |
| $X_1$: Consumption | Bigemap | The density of POIs, including all restaurants, hostels, and stores, represents the service level of consumption for visitors. | Yiqun Shang et al. [38] |
| $X_2$: Non-consumption | Bigemap | The density of POIs, including all facilities and attractions, represents the service level of non-consumption for visitors. | |
| Spatial factor | | | |
| $X_3$: Connectivity | OSM, UAV | Connectivity represents how many spaces are directly connected to the starting space. The angular connectivity offers a better description of space relationships by considering the weight of each connected space according to the turn angle. | Isabelle Soares et al. [39] Cha Ersi et al. [42] |
| Integration ($X_4$: NAINr200m, $X_5$: NAINr1000m) | OSM, UAV | Integration represents how easily a space can be reached from other spaces. To compare systems of different sizes, normalized angular integration (NAIN) with two radii (200 and 1000 m) was taken in this study according to the range of the village scales to represent walking accessibility. | |
| Choice ($X_6$: NACHIr200m, $X_7$: NACHr1000m) | OSM, UAV | Choice is a measure of space usability that considers the potential for each segment element to be selected as the shortest path. A higher choice value indicates that the calculated space is more likely to be selected by the through-movement in the network. Similar to the integration, the normalized angular choice (NACH) with two calculation radii (200 and 1000 m) was applied to represent local usability in this study. | |
| Nature factor | | | |
| $X_8$: NDVI | UAV | NDVI indicates the vegetation growth and vegetation cover status of which value is between 0 and 1, and the closer to 1, the larger the vegetation cover and the better the vegetation growth condition (more green leaf area). | Feinan Lyu et al. [41] Cha Ersi et al. [42] |

### *2.3. Quantification and Modeling*

#### 2.3.1. Identifying the Visitor-Preferred Scenes

Online reviews from social media were often used for regional or city-scale studies because of their lack of spatially explicit information. This framework applied traditional investigation experiences obtained from on-site observation to address this problem.

We conducted three systematic observations of Huanglongxian Village on 28 April, 3 May, and 23 May 2023. The date 3 May was during the Labor Day holiday, with more visitors than on working days. Each observation often took about two hours, from the main roads and deep into the remote gray spaces to a comprehensive review of the rural forest scenes. In addition, scenes with more visitors or complex morphology were recorded through photography. These on-site observation experiences allowed us to fully recognize the details of the rural forest scenes in Huanglongxian Village.

The researcher deduced the precise geographical location of the screened photos according to systematic observation experiences with the assistance of photography. The deduction results were marked as points on the map representing visitors' preferences. It should be noticed that the marked points were the spatial visual focal points shown by the visitors' photos, not the points where visitors stood when taking photos. For example, if a visitor took a photo of Huanglong Tea House on Huanglong Tea Street, the location of Huanglong Tea House should be recorded and marked on the map instead of Huanglong Tea Street (Figure 3).

**Figure 3.** Photo screening criteria and process.

To visualize the spatial distribution pattern of visitor preferences, kernel Density Estimation (KDE) in ArcGIS was utilized to smooth out the points representing visitors' preferences. When dealing with geospatial information, KDE generates a density surface where each cell is rendered based on the kernel density at the pixel center. KDE fits a kernel function for each observed geographic point, assuming each observation is continuously spread within its kernel window [19]. In this study, the kernel estimator with kernel $K$ [43] is defined by

$$\hat{f}(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x - X_i}{h}\right) \quad (2)$$

where $h$ is the window width, the smoothing parameter, or bandwidth.

#### 2.3.2. Semantic Segmentation and Cluster Analysis of Photos

The screened photos were considered as proxies of visitor-preferred scenes, which allowed us to quantify the characteristics of these rural forest scenes using CV technology and clustering algorithm:

1. Semantic segmentation (Figure 4): Pixels of physical features of the screened photos were extracted using the Pyramid Scene Parsing Network (PSPNet) [44] model, which could accurately parse the scenes with complicated elements. In this study, PSPNet model training was based on the ADE20K dataset [45].

2. Cluster analysis: We introduced the K-means clustering algorithm to perform dimensionality reduction. The K-means algorithm minimizes the within-cluster sum of squares [46]. One of these clusters is a collection of individuals with similarities, with obvious dissimilarities among different clusters. With the help of the K-means algorithm in IBM SPSS Statistics, we could categorize the visitor-preferred scenes according to their physical features obtained from semantic segmentation and find different types of visitor-preferred rural forest scenes that share similar features proportion, which exhibit significant differences.

**Figure 4.** Semantic segmentation based on PSPNet. (**a**) Original image before semantic segmentation; (**b**,**c**) The result of semantic segmentation.

#### 2.3.3. Natural Language Processing on Comments

In this study, online comment data were taken as a proxy to understand visitors' attitudes to the rural forest scenes. The comments on Huanglongxian Village were posted by visitors voluntarily. We analyzed the visitor attitudes to the rural forest scenes according to the following steps:

1. Data cleaning: Before analysis, cleaning comments data should be performed appropriately, including removing special characters, punctuation marks, and deactivated words and performing operations such as word separation.
2. Topic modeling: The Latent Dirichlet Allocation-based Natural Language Processing (LDA-NLP), a semantic extraction approach, was utilized to extract the comments topic according to different ratings. LDA-NLP helped to decompose the comments into various topics and determine the distribution of each document on each topic. By referring to the perplexity score, we can determine the number of topics to be extracted. A lower perplexity score indicates better generalization performance. For a test set of $M$ documents, the perplexity is as follows:

$$perplexity(D_{test}) = \exp\left\{-\frac{\sum_{d=1}^{M} \log p(w_d)}{\sum_{d=1}^{M} N_d}\right\} \quad (3)$$

where $p(w_d)$ refers to the probability of occurrence of each word in the test set.

3. Sentiment analysis: After topic modeling, each topic contained a certain amount of topic words. Then, we categorized topic words into positive, neutral, and negative sentiments, and the visitor's attitudes towards the topics were uncovered by counting the number of topic words under different categories.

#### 2.3.4. Geodectector Analysis

Spatial Stratified Heterogeneity (SSH) is a phenomenon in which the within strata is more similar than the between strata and ubiquitous in rural phenomena. Geodetector, or Geographical Detector, is a tool of spatial statistics to measure SSH and to make attributions for or by SSH and can explicitly reveal the association between rural forest scenes and visitors' preference without assuming linearity of the association and with clear physical meanings [47,48]. The analysis tasks can be accomplished using the Geodetector $q$-statistic:

$$q = 1 - \frac{1}{N\sigma^2} \sum_{h=1}^{L} N_h \sigma_h^2 \quad (4)$$

where the population Explained Variable (Y) is composed of $L$ strata ($h$ = 1, 2, . . ., $L$); N and $\sigma^2$ stand for the number of units and the variance of Y in a study area, respectively; $[(N - L)q]/[(L - 1)(1 - q)] \sim F(L - 1, N - L, g)$, and $g$ is a non-central parameter [47].

Before detecting the association analysis, we divided the study area into a grid of 5 m resolution, according to which the Explained Variable (Y) and Explanatory variables ($X_s$) were sampled (Table 1).

In this study, the factor detector and the interaction detector tools from Geodetector were incorporated:

1. The factor detector [47] $q$-statistic measures the degree of spatial stratified heterogeneity of a Y if Y is stratified by itself and the determinant power of an explanatory variable ($X_n$) on Y if Y is stratified by $X_n$;
2. The interaction detector [47] reveals whether the risk factors $X_1$ and $X_2$ (and more) have an interactive influence on Y. The format of the results for the interaction detector has five intervals, and the interaction relationship is determined using the location of $q(x \cap y)$ in the five intervals (Table 2).

**Table 2.** Interaction between Explanatory Variables (Xs).

| Description | Interaction |
|---|---|
| $q(X_1 \cap X_2) < \text{Min}(q(X_1), q(X_2))$ | Weaken, nonlinear |
| $\text{Min}(q(X1), q(X_2)) < q(X_1 \cap X_2) < \text{Max}(q(X_1)), q(X_2))$ | Weaken, uni- |
| $q(X_1 \cap X_2) > \text{Max}(q(X_1), q(X_2))$ | Enhance, bi- |
| $q(X_1 \cap X_2) = q(X_1) + q(X_2)$ | Independent |
| $q(X_1 \cap X_2) > q(X_1) + q(X_2)$ | Enhance, nonlinear |

## 3. Results

### *3.1. Result of Identifying the Visitor-Preferred Scenes*

Obtained using web-crawling Python script from the Dianping website, the total number of visitor-rated photos uploaded from 1 July 2013 to 25 May 2023 was 6637. After conducting the noise-reduction standards to screen these photos, valid photos ($n$ = 905) in the sample were identified and marked on the map to reflect the visitor-preferred scenes. After being geo-processed by KED, the visitors' preference was divided into six grades using Quantile in ArcGIS (Figure 5). The high values, concentrated in the middle of the village, show a linear spatial distribution in an east–west direction. This suggests that visitors' preference for rural forest scenes in Huanglongxian Village was extremely uneven.

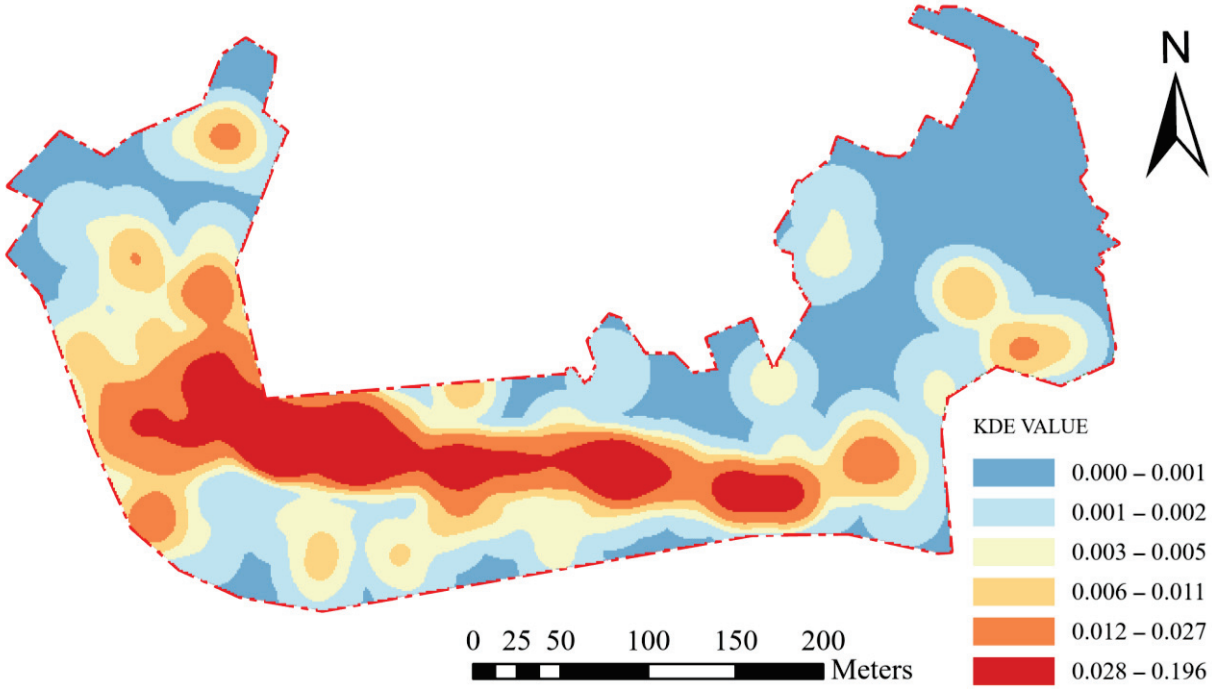



**Figure 5.** The spatial distribution of visitors' preferences.

### *3.2. Result of Semantic Segmentation and Cluster Analysis of Photos*

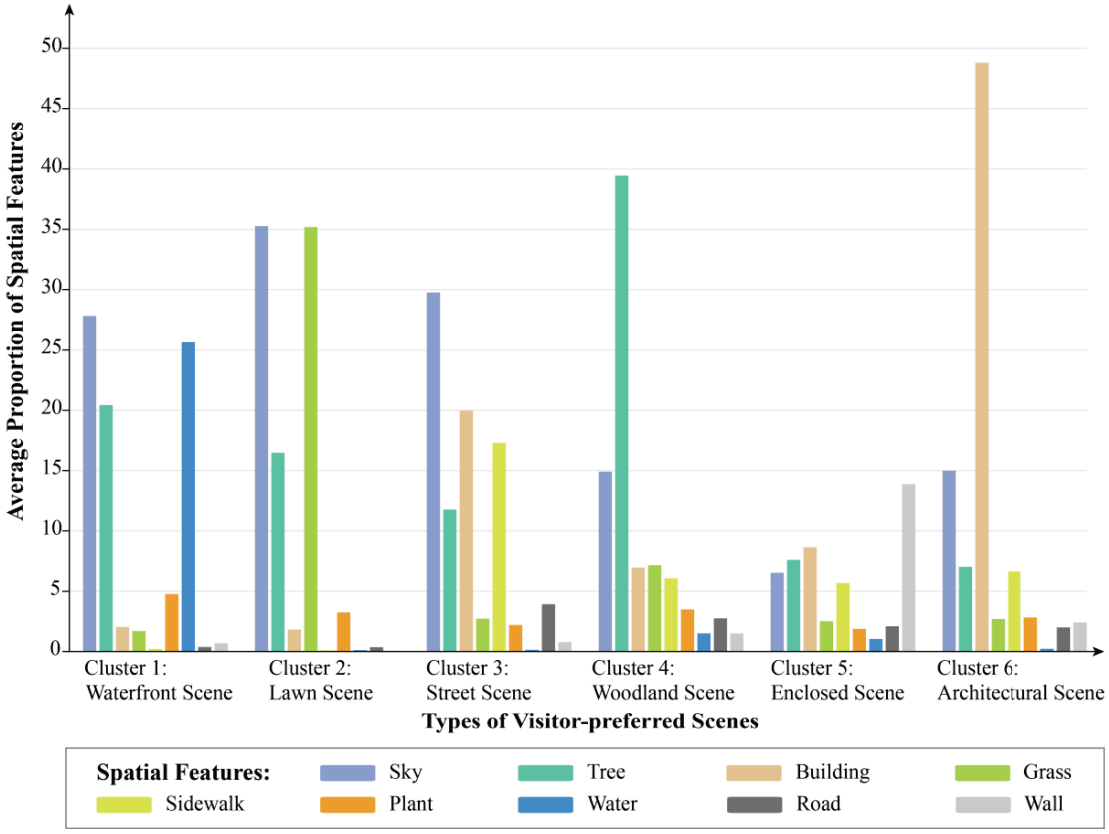
After being segmented, physical features of the 905 screened photos, such as sky, building, tree, grass, sidewalk, water, plant, wall, etc., were marked in the image, and the proportion of each feature in the photo was recorded in detail.

Analyzing Table 3, when there are too few clusters, not all types of visitor-preferred scenes can be distinguished, and when there are too many clusters, some clusters cannot be interpreted into specific scene types. To ensure the variability between each group and to avoid dispersing the classification too much, this study considered the selection of 6 clusters.

**Table 3.** Number of cases per cluster with different divisions of clusters.

| | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 | Cluster 5 | Cluster 6 | Cluster 7 | Cluster 8 |
|---|---|---|---|---|---|---|---|---|
| 2 Clusters | 490 | 415 | | | | | | |
| 3 Clusters | 329 | 182 | 394 | | | | | |
| 4 Clusters | 283 | 162 | 80 | 380 | | | | |
| 5 Clusters | 208 | 100 | 142 | 169 | 286 | | | |
| 6 Clusters | 80 | 144 | 275 | 179 | 82 | 145 | | |
| 7 Clusters | 157 | 182 | 133 | 149 | 76 | 147 | 61 | |
| 8 Clusters | 161 | 137 | 130 | 144 | 61 | 91 | 112 | 69 |

Figure 6 illustrates the average proportion of physical features among six clusters, based on which six types of visitor-preferred scenes with distinguishing physical feature proportions can be identified: waterfront scene, lawn scene, street scene, woodland scene, enclosed scene, and architectural scene.




(**a**)

(**b**)

**Figure 6.** Six types of visitor-preferred scenes. (**a**) The average proportion of physical features among six clusters; (**b**) examples of photos among six types of scenes.

### *3.3. Result of Natural Language Processing on Comments*

We collected 1356 comments from the Dianping website, which visitors voluntarily posted. The users' IDs and the time of the reviews were also recorded as attached information to distinguish each visitor.

In this study, the perplexity, used by convention in language modeling, is monotonically decreasing in the test data from 2 to 14 topic divisions (Figure 7). While a lower perplexity score indicates better generalization performance, overfitting results from peaked posteriors in the training set should be avoided. Accordingly, eight topics with their topic words were extracted from 1356 comments: facilities, nature, tourism, tea culture, lawn, leisure, and consumption (Table 4).

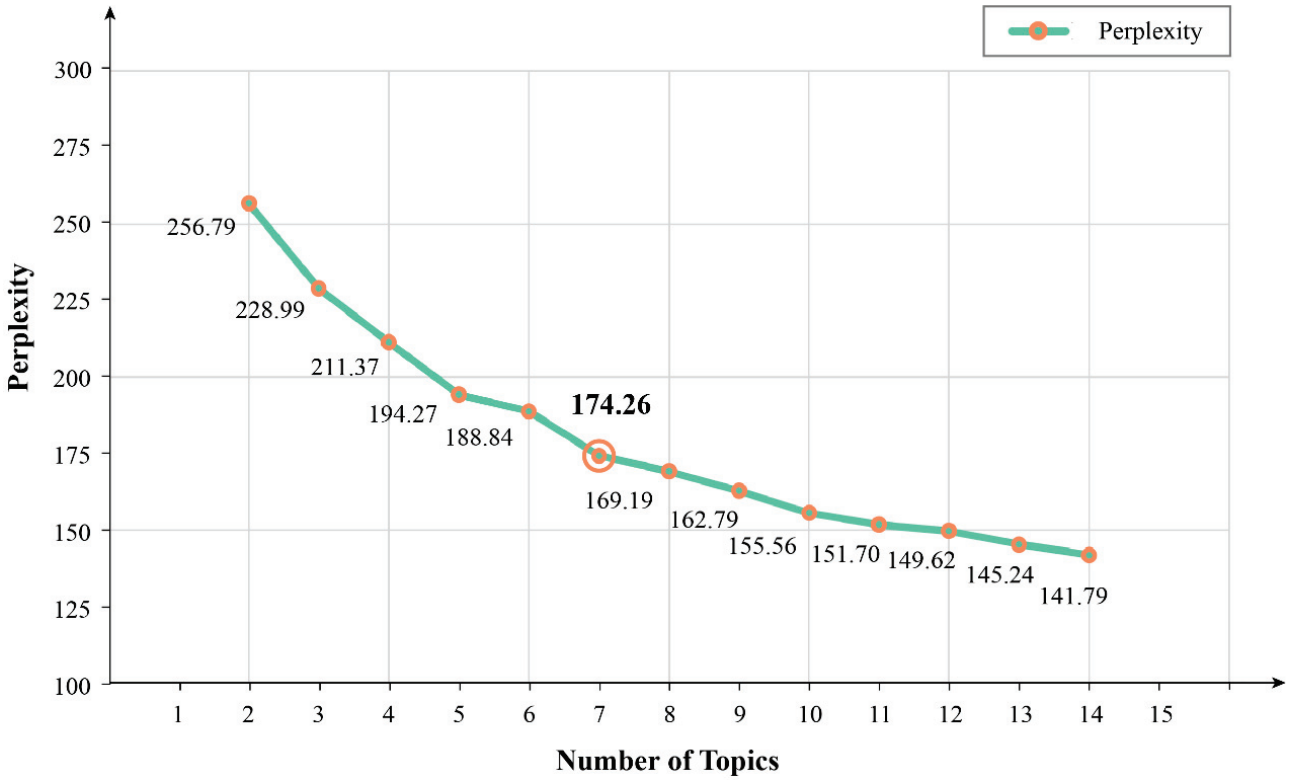



**Figure 7.** The trend of perplexity with the number of topics.

**Table 4.** Topic extraction results for visitors' comments.

| Topic Names | Comments Count | Topic Words |
|---|---|---|
| Facilities | 157 | Restroom, Farm, Walking paths, Store, etc. |
| Nature | 176 | Fresh air, Tea mountains, Lake, Bamboo Forest, etc. |
| Tourism | 194 | Scenic spots, Commercial streets, Markets, Products, etc. |
| Tea Culture | 165 | Tea art, tea fields, Tea houses, Tea mountains, etc. |
| Lawn | 186 | Sunbathing, Partying, Picnicking, Kite flying, etc. |
| Leisure | 159 | Relaxation, Flower viewing, Oxygen bar, Music, etc. |
| Consumption | 196 | Teahouse, Shops, Hotels, Restaurants, etc. |

As Figure 8 demonstrates, visitors expressed predominantly positive sentiments under most topics, especially in the facilities topic (69.35% positive sentiment) and nature topic (59.46% positive sentiment), which means that the facilities and greening construction in Huanglongxian Village can satisfy visitors. However, most visitors expressed negative (39.4%) or neutral (30.3%) sentiments about the tea culture, although Huanglongxian is a tourist village featuring the Jinling tea culture.

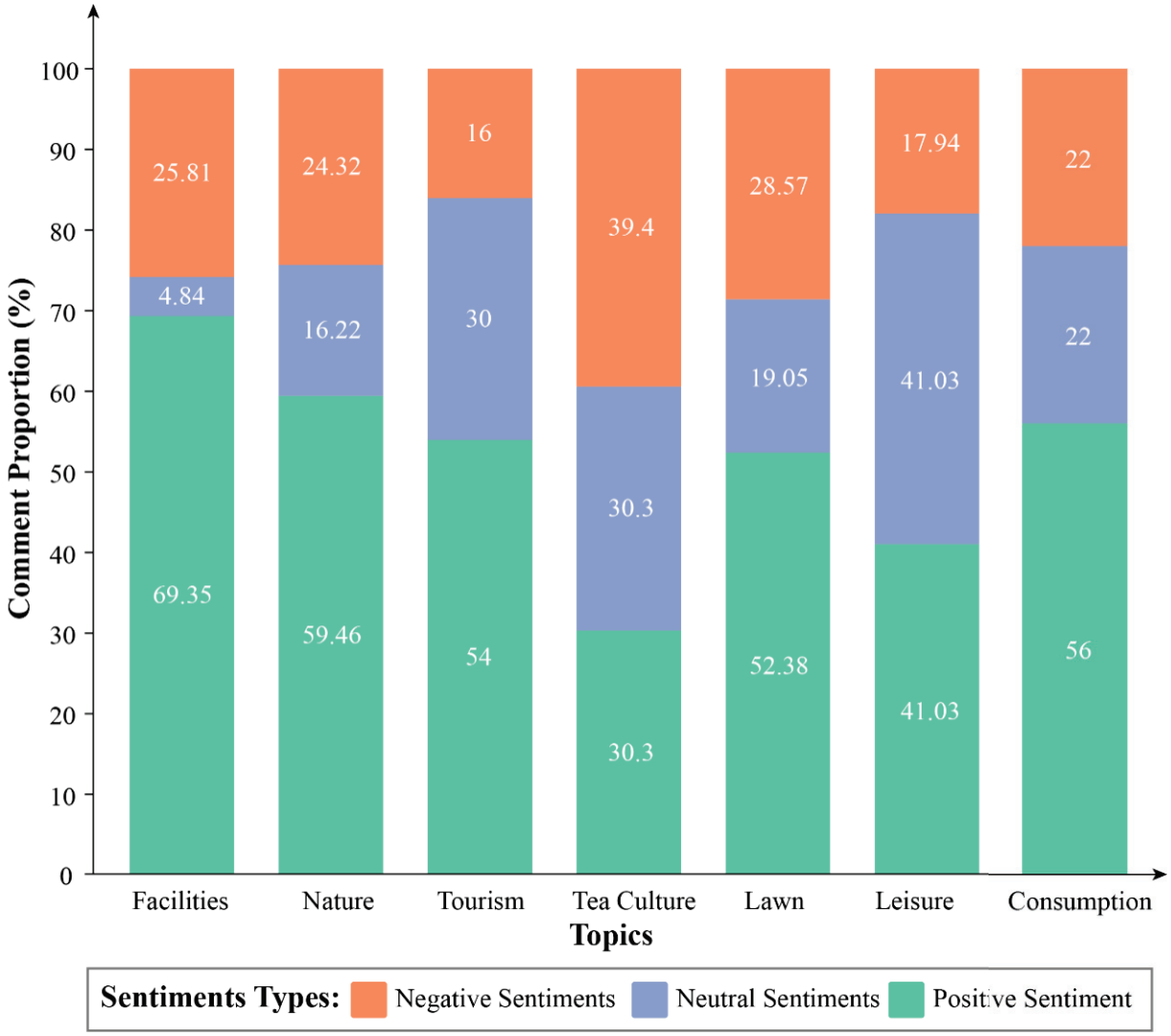



**Figure 8.** Distribution of visitors' attitudes under different topics.

### *3.4. Result of Factors of Rural Forest Scene Extraction*

1. Socio-economic factor: The total amount of POIs collected from Bigemap is 83, including 46 consumption POIs (of all restaurants, hotels, and stores) and 37 non-consumption POIs (of all facilities and attractions). As Figure 9 shows, the visualization results of the two types of POIs processed by KDE demonstrate a significant spatial variation: while high-service-level areas of consumption are concentrated on the west side of Huanglong Tea Street, high-service-level areas of non-consumption are mainly located in the eastern part of the village.
2. Spatial factor: As previous research reported [49], there is a certain degree of collinearity between space syntax indicators (Table 5). The distribution of five spatial configuration indicators geo-processed by KED is depicted in Figure 9. The high-value areas of these five indicators, representing more convenient spatial configuration areas, are concentrated in the center of the village, especially the entrance. The result of these five indicators can explain spatial properties from diverse perspectives. Connectivity is relatively independent of the other indicators (Person coefficient < 0.3, Sig. < 0.01) (Table 5). The high value of connectivity, which represents how many spaces are directly connected to the starting space, is more dispersed in spatial distribution, and the areas with high connectivity are relatively small. NACH and NAIN are all significantly correlated with each other (Sig. < 0.01) (Table 5). NAIN and NACH, which represent visitors' accessibility and usability, respectively, are significantly affected by

the calculation radius (R). With a small radius (R = 200 m), the calculated values indicate local walking behavior (<5 min), and with an increase in the radius (R = 1000 m), the calculated values reflect approximately 15–20 min walk behavior [40].

3. Natural factor: The final 175 site photos with a resolution of 4000 × 3000 pixels per image were captured by UAV. After being imported into Pix4Dmapper software, 170 out of 175 (97%) photos were calibrated, and 175 out of 175 (100%) images were geolocated to get the fine-scaled DOM of the village with the WGS-84 coordinate system. As Figure 9 shows, NDVI obtained from the band calculations of the DOM indicates the vegetation growth and cover status of Huanglongxian Village. The value of NDVI is scattered between 0 and 1, and the average NDVI value is closer to 1, which means that the vegetation growth (green leaf area) and vegetation cover of Huanglongxian Village are well-maintained overall. There is not much difference in greening level.

**Table 5.** Result of Pearson correlation between spatial factor indicators.

| | Connectivity | NAINr200m | NAINr1000m | NACHIr200m | NACHr1000m |
|---|---|---|---|---|---|
| Connectivity | 1.000 | | | | |
| NAINr200m | 0.151 ** | 1.000 | | | |
| NAINr1000m | 0.114 ** | **0.767** ** | 1.000 | | |
| NACHIr200m | 0.270 ** | **0.533** ** | 0.435 ** | 1.000 | |
| NACHr1000m | 0.279 ** | **0.577** ** | **0.544** ** | **0.955** ** | 1.000 |

Note: ** represents a significant correlation at 0.01 level. Correlation coefficients > 0.5 are bolded.

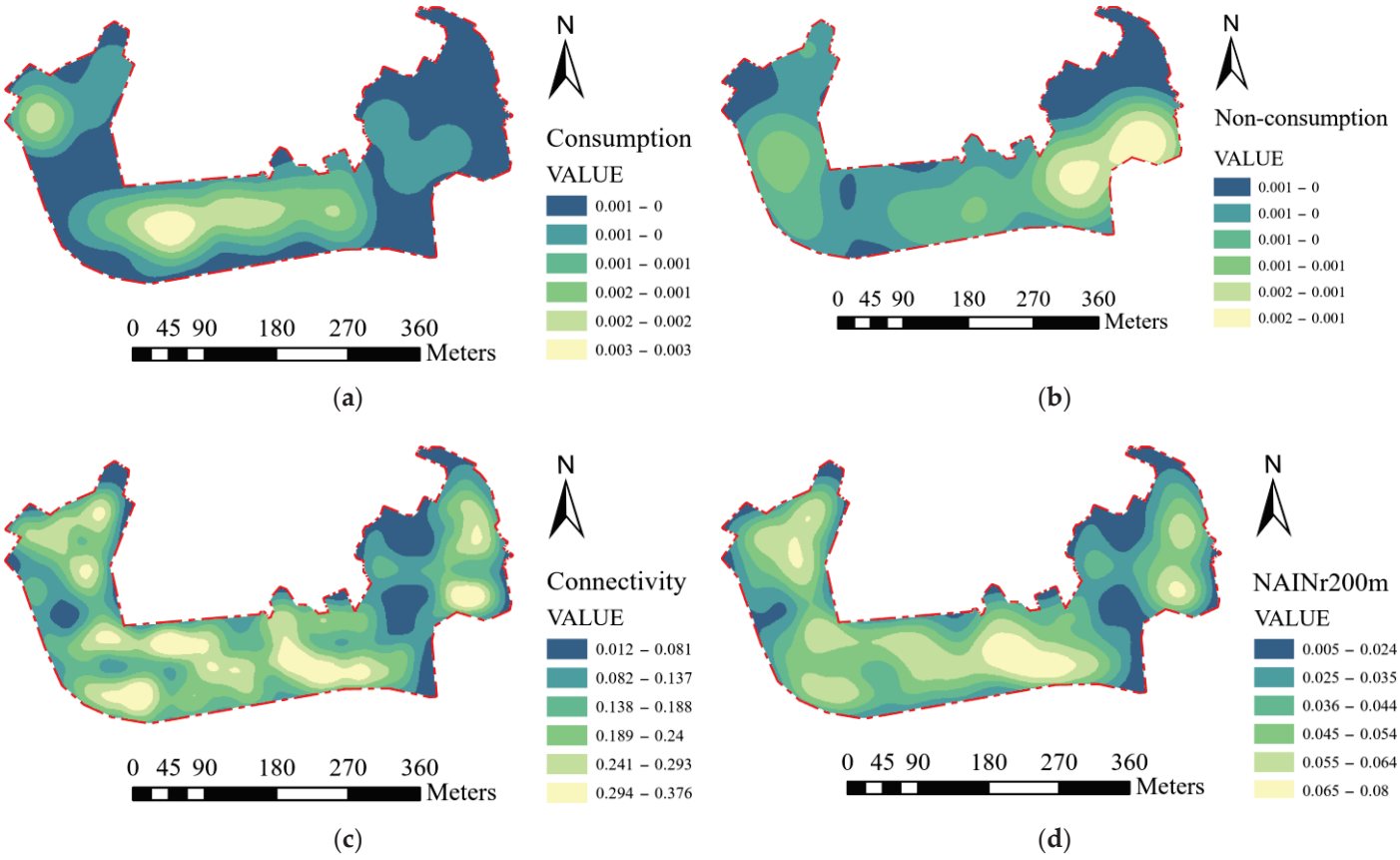



**Figure 9.** *Cont.*

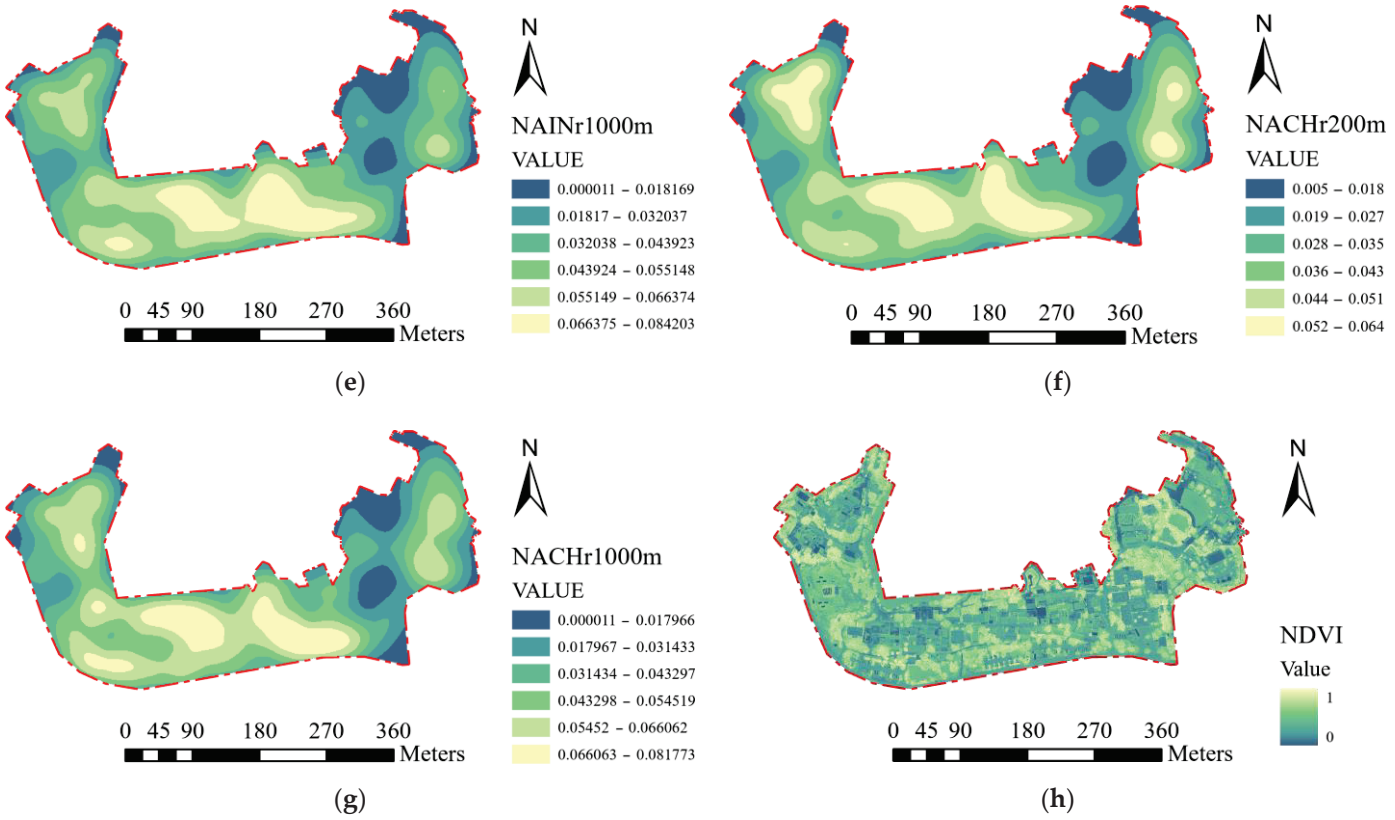



**Figure 9.** Results of factors extraction. (**a**,**b**) Results of socio-economic factor extraction; (**c**–**g**) results of spatial factor extraction; (**h**) results of natural factor extraction.

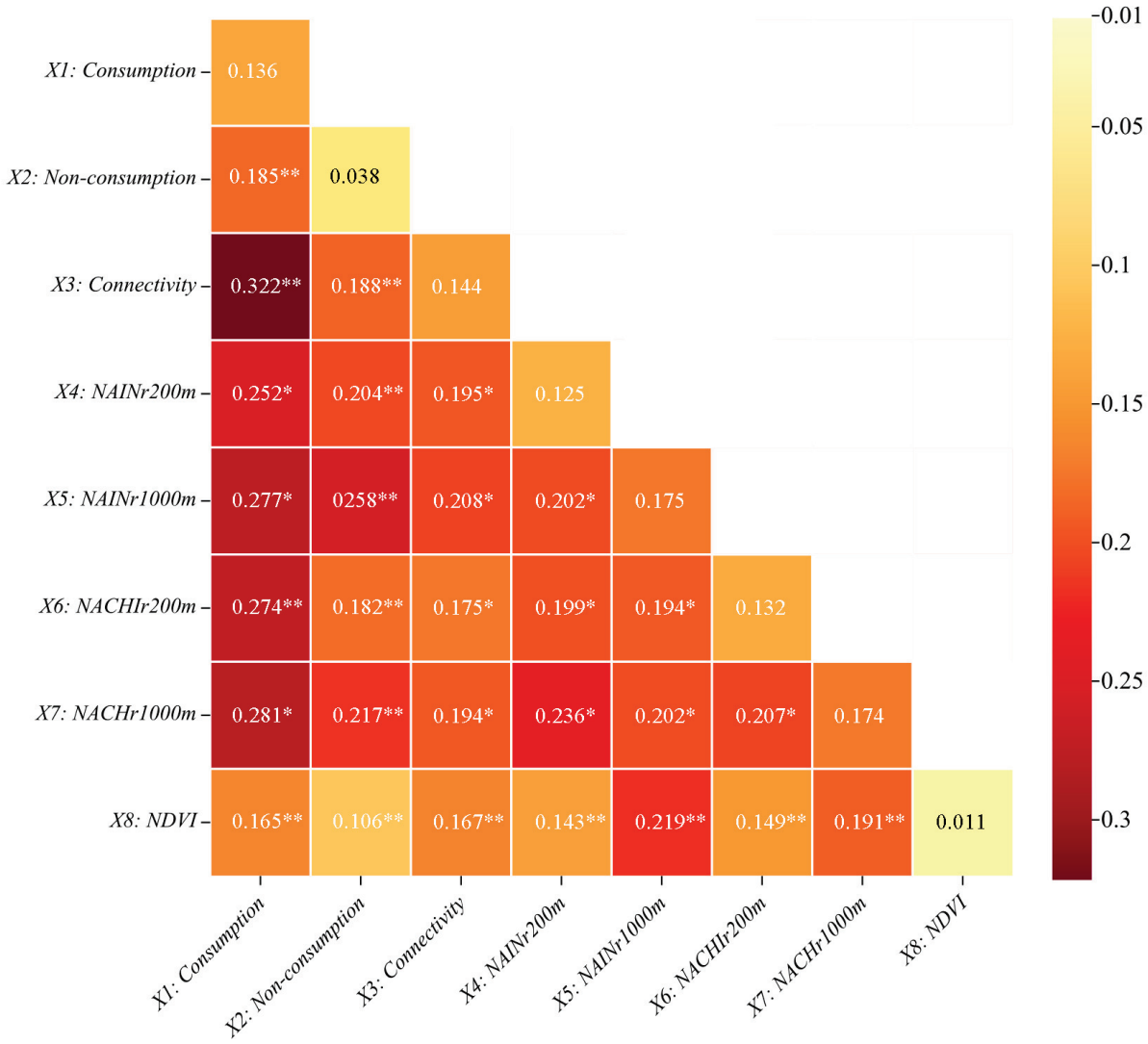
### *3.5. Result of Geodectector Analysis*

Factor detection results (Table 6) demonstrate that the significance levels for all eight indicators are less than 0.0, but their *q*-statistics values are below 0.2. The *q*-statistics values of indicators from spatial factor all exceed 0.1, among which NAINr1000m (*q*-statistics = 0.175, Sig. < 0.01) and NACHr1000m (*q*-statistics = 0.174, Sig. < 0.01) are the highest, and NAINr200m (*q*-statistics = 0.125, Sig. < 0.01) and NACHr200m (*q*-statistics = 0.132, Sig. < 0.01) are relatively lower. Additionally, *q*-statistics of connectivity (*q*-statistics = 0.144, Sig. < 0.01) is the third highest. When it comes to socio-economic factor, the *q*-statistics values of consumption (*q*-statistics = 0.136, Sig. < 0.01) is significantly higher than non-consumption support (*q*-statistics = 0.038, Sig. < 0.01). Among eight factors, the *q*-statistics values of non-consumption and NDVI (*q*-statistics = 0.011, Sig. < 0.01) are the lowest (no more than 0.05).

**Table 6.** Results of factor detector.

| | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ |
|---|---|---|---|---|---|---|---|---|
| | **Consumption** | **Non-Consumption** | **Connectivity** | **NAINr200m** | **NAINr1000m** | **NACHIr200m** | **NACHr1000m** | **NDVI** |
| *q*-statistics | 0.136 | 0.038 | 0.144 | 0.125 | 0.175 | 0.132 | 0.174 | 0.011 |
| *p*-value | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Interactive detection results of factors are shown in Figure 10. The interaction detector helps to check whether two indicators work independently or not, and all indicators of three types of factors are found to enhance each other to increase the visitors' preference ($q(A \cap B) > \text{Max}(q(A), q(B))$). NDVI and non-consumption should be noticed when each of them is combined with other indicators, and they can produce non-linear enhancements on visitors' preference ($q(A \cap B) > (q(A) + q(B))$). Additionally, the interactions between consumption and connectivity, NACHr200m, are also nonlinear enhanced ($q(A \cap B) > (q(A) + q(B))$).




Notes: **. indicates two indicators nonlinear enhancement, i. e. q(A∩B) > (q(A)+q(B)) ;
*. indicates bilinear enhancement of two indicators,i.e. Max(q(A), q(B)) < q(A∩B) < (q(A)+q(B)).

**Figure 10.** Results of interaction detector.

## 4. Discussion

### *4.1. Comprehensively Description of Visitors' Feedback*

This study reverses the status of visitors and researchers. In this study, each visitor's feedback was fully valued, and the expert only played a role in organizing and analyzing the visitor's reviews. Utilizing visitors' voluntarily uploaded reviews (including comments and photos) on social media saves the cost of collecting visitors' feedback and greatly expands the study's sample size [18–20]. This provides the foundation for comprehensively describing visitors' feedback.

#### 4.1.1. Spatial Distribution of Preferred Rural Forest Scenes

In traditionally survey-based studies, the researcher commonly pre-set several types of scenes for visitors to judge their preferences [8]. Additionally, the expert experience occupied a decisive position [9], and therefore, some visitor-preferred scenes may be overlooked. In contrast to previous studies, this study shifts the opportunity for scene selection to visitors themselves by taking photos voluntarily posted by all visitors into consideration.

Photos screened by "noise" reduction criteria comprehensively reflect the visitor-preferred rural forest scenes in Huanglongxian Villages. As Figure 5 shows, Huanglong

Tea Street, especially at the entrance and on the waterfront (the red area in the figure), are visitors' most preferred outdoor scenes in Huanglongxian village. Compared with the popular scenes, many scenes (the blue area in the figure) hardly appear in the photos of visitors, which demonstrates that these scenes are neglected and not preferred enough by visitors. At the scale of the whole village, the level of visitors' preference decreases from the east–west street in the center of the village to the surrounding area. However, there are exceptions in local areas, such as the areas near tourist service centers, hotel-concentrated regions, and children's playgrounds, where there are localized high values in the level of visitor preference.

#### 4.1.2. Scenes Characteristics of Preferred Rural Forest Scenes

In previous studies, the characteristics of scenes were described by researchers according to pre-set scenes before collecting visitors' feedback [9,12]. This study tunes the sequence of describing scene characteristics. This study analyzed the characteristics of visitor-preferred scenes based on visitors' feedback using CV technology and clustering algorithm so that we can quantitatively understand the characteristics of visitor-preferred rural forest scenes as follows:

1. In the waterfront scene, the sky and the water are dominant, accompanied by trees along the shore of Huanglong Lake.
2. The lawn scene is Huanglong Square, a great lawn covered by trample-resistant grass with sparse dwarf trees. The lawn scene gives visitors access to enjoy the sunshine and blue sky.
3. Mainly referring to the Huanglong Tea Street and Xiaoxian Market, the street scene is visitors' most popular type of rural forest scene in Huanglongxian Village. Wide and well-greened streets are flanked by antique buildings where visitors can see the sky.
4. In the natural environment with plenty of trees, the second most popular scene is the woodland scene, with relatively less sky visibility, providing visitors with shade.
5. In the enclosed scene, the physical features are scattered, among which the wall relatively occupies a higher proportion. For example, the scene inside the Huanglong Pavilion, enclosed by low walls, offers visitors a place to rest.
6. In the architectural scene, the proportion of buildings is extremely high, which means the surroundings of native architecture with classical characteristics have a unique attraction for urban visitors.

#### 4.1.3. Visitors' Attitudes to Rural Forest Scenes

The limitation of lacking visitors' feedback in previous studies [11,14,17] can be compensated by a large number of visitor social media reviews, and these comments were auto-analyzed using the LDA-NLP model. Based on the cost savings in visitors' feedback acquisition and analysis, we can further interpret visitors' attitudes to rural forest scenes:

1. Facilities support visitors and activities, including restrooms, farms, walking paths, etc. To some extent, tourism-related and consumption-related topic words can explain visitors' preference for street scenes. Tea houses, shops, and restaurants are available in the street scene for rest, dining, and shopping.
2. Nature-related topic words indicate visitors prefer fresh air, tea mountains, lakes, and bamboo forests in waterfront and woodland scenes. Lawn-related topics words illustrate that visitors prefer the lawn scene because it supports numerous activities and access to sharing time with family and friends.
3. While the facilities and natural conditions of Huanglongxian Village already meet the needs of visitors and no additional construction is required, tea culture still needs to be optimized. Even though Huanglongxian Village is famous for the Jinling tea culture, its rural forest scenes lack elements that reflect the relevant culture, such as facilities, attractions, and services. This is why it fails to give tourists a good tea culture experience.

### 4.2. Effects of Factors in the Rural Forest Scenes on Visitors' Preferences

This study incorporates multi-source geospatial data analysis to figure out the driven factors from the perspective of rural forest scene factors. Conventional regression methods [47–49] were the most common classical statistical methods in exploring how potential influencing factors affect visitors. The implications behind the multi-source geospatial data and how these implications can explain visitors' preferences are yet to be appropriately uncovered. This study thoroughly considered SSH phenomena [44], using Geodetector to disentangle the complicated relationships between eight indicators of rural forest scene factors and visitors' preferences. In addition to the natural factor, spotlighted in the urban forest scenes [8–10], this study extends to socio-economic and spatial factors.

#### 4.2.1. Explanation Power of the Singe Factor in Rural Forest Scenes

From the perspective of a single indicator, although the explanatory power of each indicator is not as strong, the indicators of spatial factors have a more robust interpretation of visitors' preferences. On the one hand, accessibility (reflected by NAIN) and usability (reflected by NACH) under the waking range area can be identified as the main driving power for the visitors' preference in Huanglongxian Village. On the other hand, compared to the 2–3 min walk (which is the 200 m walking range), the 10–15 min walk (which is the 1000 m walking range) behavior is more likely to occur in Huanglongxian Village. Additionally, connectivity, to some extent, is also strongly associated with visitors' preferences. These spatial indicators also reflect the transport condition within the village. And the results illustrate the equal importance of taking visitors to the different attractions and bringing visitors to the destination [23].

Regarding indicators of socio-economic factors, consumption support has significantly stronger explanatory power than non-consumption support for the visitors' preference. Compared with non-consumption scenes such as scenic spots, planners should improve the construction of consumption scenes. This is not only an urgent need for visitors, but also a measure to promote the village's economic growth.

Opposed to the conclusions obtained from studies in urban forest scenes, the natural factor has weak explanatory power for visitors' preferences in rural forest scenes. Surrounded by Huanglong Lake and tea mountains, the natural environment throughout the village is already excellent compared to the urban forest scenes.

#### 4.2.2. Interactive Effect of Factors in Rural Forest Scenes

From the perspective of an interactive detector, the combination of each of the two indicators of rural forest scene factors explains the distribution of visitors' preferences better than a single indicator. It means that rational combinations between the various sources of the village can be more effective for visitors' preferences. Moreover, although NDVI and Non-consumption barely explain visitors' preference solely, combining them with other indicators can produce a non-linear enhancement effect on visitors' preference. Although slight differences in vegetation cover have little impact on visitors' perceptions, a pleasant natural environment, and non-consumptive attractions are the basis for villages to be able to attract visitors.

### 4.3. Theoretical Implications

From the technical perspective, in addition to the experience from traditional on-site surveys, this study fully utilizes interdisciplinary technologies and develops and validates a framework to transform social media and multi-source geospatial data into interpretable outcomes for visitors' preferences in rural forest scenes. The data-fusion framework in this study consequently addresses traditional face-to-face surveys' high monetary and time costs with low response rates [8,17]. Additionally, this data-fusion framework proposes a paradigm compatible with other types of data analysis methods and can be further optimized for different study purposes, such as business and commercial data, transportation and traffic data, and sports tracking data [50,51].

From the scope perspective, this study broadens the understanding of visitors' preferences from urban forest scenes to rural forest scenes. This study tests and completes the conclusions drawn in the urban forest scenes: natural factors that play an important role in urban forest scenes [10] may fail to solely exert a significant influence on visitors' preferences in rural forest scenes. In addition to natural factors, this study further expands the indicators of socio-economic and spatial factors.

### *4.4. Practical Implications*

This study, fully utilizing interdisciplinary technologies, explores visitors' preferences in rural forest scenes. The findings broaden the understanding of visitors' preference in rural forest scenes and provide empirical evidence for rural planners to develop a visitor-attractive village from the perspective of socio-economic, spatial, and natural factors.

First of all, our study revealed that although socio-economic and spatial factors are not emphasized in the urban forest scenes, they are relevant to the visitors' preference for rural forest scenes. Planners should be concerned about the socio-economic environment and spatial configurations. For example, visitors should be given more opportunities for consumption, and accessibility and usability should be considered when planning village roads.

Second, there should be some restraint on the greening of villages. This is because the effect of simply adding greenery to a rural forest scene on visitor preferences is insignificant. This places requirements on planners for the quality of greenery in addition to its quantity. Designing planted landscapes at the entrance to the village or on the street is more responsive to visitors' needs than planting trees in groups.

Third, planners should think holistically about the various resources in the rural forest scenes. Analyzing the interactive effect between factors closely related to village construction, planners should contribute to human-centered village development by finding a new path for rationalizing the allocation of these factors.

### *4.5. Limitations*

There are several limitations in this study. First, potential biases from social media data may hinder the full representation of all visitors' feedback in Huanglongxian Village. The demographic details of visitors are not available on social media for personal privacy reasons. Feedback from people such as elderly children may make it harder to appear on social media because they do not use smartphones. Previous studies have shown that differences in visitors' attributes, including visitors' age, place of residence, destination stay time, return visits, etc., can lead to differences in tourist perceptions [52] and the sentiments they may convey [53]. Second, this study may not have sufficiently refined the identification of rural forest scenes. Because the ADE20K dataset was used for training the CV model in this study, it lacked sufficient training data for rural forest scene identification [45]. Future studies could improve the accuracy of identifying the physical features of rural forest scenes by producing datasets and labeling the training data as needed. Third, "cultural landscape" is another important concept of rural forest scene but less emphasized in this study compared with "natural landscape". Huanglongxian Village has an abundance of cultural resources and has witnessed the human influence over time. Consequently, the cultural landscapes in Villages like Huanglongxian can be further studied in the future. Finally, geospatial data quality exhibited spatial heterogeneity [54], with fewer qualified data in the countryside compared to developed areas [55]. For example, as a type of Volunteered Geographic Information (VGI) [54,55], street networks from OSM were created by large numbers of citizens, mostly with no formal training [56]. Although street networks were manually amended and supplemented based on UAV remote sensing in this study, the accuracy of the results needs to be verified in subsequent studies.

## 5. Conclusions

This study developed a data-fusion framework to broaden the scope of understanding visitors' preferences in rural forest settings. At the methodological level, empirical research implemented in Huanglongxian Village demonstrates the efficiency of social media and multi-source geospatial data in understanding visitors' preferences compared with traditional approaches. At the level of the study subject, this study expanded from urban forest scenes to rural forest scenes. Contrary to the urban forest scenes, findings in rural forest scenes suggest that the natural factor does not significantly impact visitors' preferences, and the spatial factor has a more robust interpretation. At the level of research depth, this study explores the influence of three types of indicators, including socio-economic factors, spatial factors, and natural factors. The combination of indicators can have a more substantial effect on visitors' preferences than a single indicator. Consequently, the insight gained from this study will help achieve a more scientific decision-making process toward developing villages by instructing the village planning to meet the factual demand.

**Author Contributions:** Conceptualization, C.W. and S.C.; methodology, C.W. and S.C.; software, C.W.; validation, C.W., J.Z. and S.C.; formal analysis, C.W.; investigation, C.W., J.Z. and X.F.; resources, J.Z.; data curation, X.F.; writing—original draft preparation, C.W.; writing—review and editing, C.W.; visualization, C.W. and J.Z.; supervision, H.W.; project administration, H.W.; funding acquisition, H.W. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the "National Key Research and Development Program of China" (Grant No.2019YFD1100404): Research on the construction and application technology of rural plant landscape, "National Natural Science Foundation of China" (Grant No.52308066), "Jiangsu Province Universities Natural Sciences Foundation" (Grant No. 23KJB560018), and "A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions" (PAPD).

**Data Availability Statement:** The data presented in this study are available upon request from the author. Images employed for the study will be available online for readers.

**Acknowledgments:** We would particularly like to acknowledge Hongchao Jiang for inspiring our interest in developing innovative technologies. In addition, we would like to acknowledge Bingchen Tong for her guidance on statistical methods for processing and analyzing social media data.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Zhang, F.; Wang, N.; Li, Q. Low-Carbon Space in Urban and Rural Areas: Ecological Greenway Planning of Shanhaiguan District, Qinhuangdao City, China. *Appl. Mech. Mater.* **2013**, *253–255*, 821–824. [CrossRef]
2. Lan, Y.; Liu, Q.; Zhu, Z. Exploring Landscape Design Intensity Effects on Visual Preferences and Eye Fixations in Urban Forests: Insights from Eye Tracking Technology. *Forests* **2023**, *14*, 1628. [CrossRef]
3. Sun, Y.; Shao, Y.; Chan, E.H.W. Co-Visitation Network in Tourism-Driven Peri-Urban Area Based on Social Media Analytics: A Case Study in Shenzhen, China. *Landsc. Urban Plan.* **2020**, *204*, 103934. [CrossRef]
4. Su, T.; Wang, K.; Li, S.; Wang, X.; Li, H.; Ding, H.; Chen, Y.; Liu, C.; Liu, M.; Zhang, Y. Analysis and Optimization of Landscape Preference Characteristics of Rural Public Space Based on Eye-Tracking Technology: The Case of Huangshandian Village, China. *Sustainability* **2022**, *15*, 212. [CrossRef]
5. Kastenholz, E.; Eusebio, C.; Carneiro, M.J. Segmenting the Rural Tourist Market by Sustainable Travel Behaviour: Insights from Village Visitors in Portugal. *J. Destin. Mark. Manag.* **2018**, *10*, 132–142. [CrossRef]
6. Gao, C.; Cheng, L.; Iqbal, J.; Cheng, D. An Integrated Rural Development Mode Based on a Tourism-Oriented Approach: Exploring the Beautiful Village Project in China. *Sustainability* **2019**, *11*, 3890. [CrossRef]
7. Tu, S.; Long, H.; Zhang, Y.; Ge, D.; Qu, Y. Rural Restructuring at Village Level under Rapid Urbanization in Metropolitan Suburbs of China and Its Implications for Innovations in Land Use Policy. *Habitat Int.* **2018**, *77*, 143–152. [CrossRef]
8. Arnberger, A.; Eder, R. Are Urban Visitors' General Preferences for Green-Spaces Similar to Their Preferences When Seeking Stress Relief? *Urban For. Urban Green.* **2015**, *14*, 872–882. [CrossRef]
9. Li, C.; Shen, S.; Ding, L. Evaluation of the Winter Landscape of the Plant Community of Urban Park Green Spaces Based on the Scenic Beauty Esitimation Method in Yangzhou, China. *PLoS ONE* **2020**, *15*, e0239849. [CrossRef]
10. Santosa, H.; Ernawati, J.; Wulandari, L.D. Visual Quality Evaluation of Urban Commercial Streetscape for the Development of Landscape Visual Planning System in Provincial Street Corridors in Malang, Indonesia. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *126*, 012202. [CrossRef]

11. Wilkins, E.J.; Van Berkel, D.; Zhang, H.; Dorning, M.A.; Beck, S.M.; Smith, J.W. Promises and Pitfalls of Using Computer Vision to Make Inferences about Landscape Preferences: Evidence from an Urban-Proximate Park System. *Landsc. Urban Plan.* **2022**, *219*, 104315. [CrossRef]
12. Jay, M.; Schraml, U. Understanding the Role of Urban Forests for Migrants—Uses, Perception and Integrative Potential. *Urban For. Urban Green.* **2009**, *8*, 283–294. [CrossRef]
13. Sonti, N.F.; Campbell, L.K.; Svendsen, E.S.; Johnson, M.L.; Novem Auyeung, D.S. Fear and Fascination: Use and Perceptions of New York City's Forests, Wetlands, and Landscaped Park Areas. *Urban For. Urban Green.* **2020**, *49*, 126601. [CrossRef]
14. Southon, G.E.; Jorgensen, A.; Dunnett, N.; Hoyle, H.; Evans, K.L. Biodiverse Perennial Meadows Have Aesthetic Value and Increase Residents' Perceptions of Site Quality in Urban Green-Space. *Landsc. Urban Plan.* **2017**, *158*, 105–118. [CrossRef]
15. Heyman, E. Analysing Recreational Values and Management Effects in an Urban Forest with the Visitor-Employed Photography Method. *Urban For. Urban Green.* **2012**, *11*, 267–277. [CrossRef]
16. Du, H.; Jiang, H.; Song, X.; Zhan, D.; Bao, Z. Assessing the Visual Aesthetic Quality of Vegetation Landscape in Urban Green Space from a Visitor's Perspective. *J. Urban Plan. Dev.* **2016**, *142*, 04016007. [CrossRef]
17. Arnberger, A.; Budruk, M.; Schneider, I.E.; Wilhelm Stanis, S.A. Predicting Place Attachment among Walkers in the Urban Context: The Role of Dogs, Motivations, Satisfaction, Past Experience and Setting Development. *Urban For. Urban Green.* **2022**, *70*, 127531. [CrossRef]
18. Xiang, Z.; Gretzel, U. Role of Social Media in Online Travel Information Search. *Tour. Manag.* **2010**, *31*, 179–188. [CrossRef]
19. Huang, Y.; Li, Z.; Huang, Y. User Perception of Public Parks: A Pilot Study Integrating Spatial Social Media Data with Park Management in the City of Chicago. *Land* **2022**, *11*, 211. [CrossRef]
20. Li, Q.; Wu, Y.; Wang, S.; Lin, M.; Feng, X.; Wang, H. VisTravel: Visualizing Tourism Network Opinion from the User Generated Content. *J. Vis.* **2016**, *19*, 489–502. [CrossRef]
21. Chan, H.K.; Wang, X.; Lacka, E.; Zhang, M. A Mixed-Method Approach to Extracting the Value of Social Media Data. *Prod. Oper. Manag.* **2016**, *25*, 568–583. [CrossRef]
22. Liu, T.-J.; Lin, Y.-C.; Lin, W.; Kuo, C.-C.J. Visual Quality Assessment: Recent Developments, Coding Applications and Future Trends. *APSIPA Trans. Signal Inf. Process.* **2013**, *2*, e4. [CrossRef]
23. Mira, M.D.R.C.; Mónico, L.M.; Breda, Z.J. Territorial Dimension in the Internationalization of Tourism Destinations: Structuring Factors in the Post-COVID19. *Tour. Manag. Stud.* **2021**, *17*, 33–44. [CrossRef]
24. Psyllidis, A.; Gao, S.; Hu, Y.; Kim, E.-K.; McKenzie, G.; Purves, R.; Yuan, M.; Andris, C. Points of Interest (POI): A Commentary on the State of the Art, Challenges, and Prospects for the Future. *Comput. Urban Sci.* **2022**, *2*, 20. [CrossRef] [PubMed]
25. Chen, B.; Tu, Y.; Song, Y.; Theobald, D.M.; Zhang, T.; Ren, Z.; Li, X.; Yang, J.; Wang, J.; Wang, X.; et al. Mapping Essential Urban Land Use Categories with Open Big Data: Results for Five Metropolitan Areas in the United States of America. *Isprs J. Photogramm. Remote Sens.* **2021**, *178*, 203–218. [CrossRef]
26. Ye, Y.; Richards, D.; Lu, Y.; Song, X.; Zhuang, Y.; Zeng, W.; Zhong, T. Measuring Daily Accessed Street Greenery: A Human-Scale Approach for Informing Better Urban Planning Practices. *Landsc. Urban Plan.* **2019**, *191*, 103434. [CrossRef]
27. Kuliga, S.F.; Nelligan, B.; Dalton, R.C.; Marchette, S.; Shelton, A.L.; Carlson, L.; Hölscher, C. Exploring Individual Differences and Building Complexity in Wayfinding: The Case of the Seattle Central Library. *Environ. Behav.* **2019**, *51*, 622–665. [CrossRef]
28. Hillier, B.; Iida, S. Network and Psychological Effects in Urban Movement. In Proceedings of the Spatial Information Theory, Ellicottville, NY, USA, 14–18 September 2005; Cohn, A.G., Mark, D.M., Eds.; Springer: Berlin, Heidelberg, 2005; pp. 475–490.
29. Koohsari, M.J.; Kaczynski, A.T.; Mcormack, G.R.; Sugiyama, T. Using Space Syntax to Assess the Built Environment for Physical Activity: Applications to Research on Parks and Public Open Spaces. *Leis. Sci.* **2014**, *36*, 206–216. [CrossRef]
30. Luo, J.; Zhao, T.; Cao, L.; Biljecki, F. Semantic Riverscapes: Perception and Evaluation of Linear Landscapes from Oblique Imagery Using Computer Vision. *Landsc. Urban Plan.* **2022**, *228*, 104569. [CrossRef]
31. Albetis, J.; Duthoit, S.; Guttler, F.; Jacquin, A.; Goulard, M.; Poilvé, H.; Féret, J.-B.; Dedieu, G. Detection of Flavescence Dorée Grapevine Disease Using Unmanned Aerial Vehicle (UAV) Multispectral Imagery. *Remote Sens.* **2017**, *9*, 308. [CrossRef]
32. Liu, C.; Cao, Y.; Yang, C.; Zhou, Y.; Ai, M. Pattern Identification and Analysis for the Traditional Village Using Low Altitude UAV-Borne Remote Sensing: Multifeatured Geospatial Data to Support Rural Landscape Investigation, Documentation and Management. *J. Cult. Herit.* **2020**, *44*, 185–195. [CrossRef]
33. Donahue, M.L.; Keeler, B.L.; Wood, S.A.; Fisher, D.M.; Hamstead, Z.A.; McPhearson, T. Using Social Media to Understand Drivers of Urban Park Visitation in the Twin Cities, MN. *Landsc. Urban Plan.* **2018**, *175*, 1–10. [CrossRef]
34. Liang, H.; Yan, Q.; Yan, Y.; Zhang, L.; Zhang, Q. Spatiotemporal Study of Park Sentiments at Metropolitan Scale Using Multiple Social Media Data. *Land* **2022**, *11*, 1497. [CrossRef]
35. Kobayashi, M.; Takeda, K. Information Retrieval on the Web. *ACM Comput. Surv.* **2000**, *32*, 144–173. [CrossRef]
36. Kedzierski, M.; Wierzbicki, D. Methodology of Improvement of Radiometric Quality of Images Acquired from Low Altitudes. *Measurement* **2016**, *92*, 70–78. [CrossRef]
37. Cao, J.; Leng, W.; Liu, K.; Liu, L.; He, Z.; Zhu, Y. Object-Based Mangrove Species Classification Using Unmanned Aerial Vehicle Hyperspectral Images and Digital Surface Models. *Remote Sens.* **2018**, *10*, 89. [CrossRef]
38. Shang, Y.; Wen, C.; Bai, Y.; Hou, D. A Novel Framework for Exploring the Spatial Characteristics of Leisure Tourism Using Multisource Data: A Case Study of Qingdao, China. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2022**, *15*, 6259–6271. [CrossRef]

39. Soares, I.; Yamu, C.; Weitkamp, G. The Relationship between the Spatial Configuration and the Fourth Sustainable Dimension Creativity in University Campuses: The Case Study of Zernike Campus, Groningen, The Netherlands. *Sustainability* **2020**, *12*, 9263. [CrossRef]
40. Sheng, Q.; Wan, D.; Yu, B. Effect of Space Configurational Attributes on Social Interactions in Urban Parks. *Sustainability* **2021**, *13*, 7805. [CrossRef]
41. Lyu, F.; Zhang, L. Using Multi-Source Big Data to Understand the Factors Affecting Urban Park Use in Wuhan. *Urban For. Urban Green.* **2019**, *43*, 126367. [CrossRef]
42. Ersi, C.; Bayaer, T.; Bao, Y.; Bao, Y.; Yong, M.; Lai, Q.; Zhang, X.; Zhang, Y. Comparison of Phenological Parameters Extracted from SIF, NDVI and NIRv Data on the Mongolian Plateau. *Remote Sens.* **2023**, *15*, 187. [CrossRef]
43. Silverman, B.W. *Density Estimation for Statistics and Data Analysis*; CRC Press: Boca Raton, FL, USA, 1986; ISBN 978-0-412-24620-3.
44. Zhao, H.; Shi, J.; Qi, X.; Wang, X.; Jia, J. Pyramid Scene Parsing Network. In Proceedings of the 2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Honolulu, HI, USA, 21–26 July 2017; pp. 6230–6239.
45. Zhou, B.; Zhao, H.; Puig, X.; Xiao, T.; Fidler, S.; Barriuso, A.; Torralba, A. Semantic Understanding of Scenes through the ADE20K Dataset. *Int. J. Comput. Vis.* **2019**, *127*, 302–321. [CrossRef]
46. Hartigan, J.A.; Wong, M.A. Algorithm AS 136: A K-Means Clustering Algorithm. *J. R. Stat. Soc. Ser. C Appl. Stat.* **1979**, *28*, 100–108. [CrossRef]
47. Wang, J.-F.; Zhang, T.-L.; Fu, B.-J. A Measure of Spatial Stratified Heterogeneity. *Ecol. Indic.* **2016**, *67*, 250–256. [CrossRef]
48. Wang, J.; Li, X.; Christakos, G.; Liao, Y.; Zhang, T.; Gu, X.; Zheng, X. Geographical Detectors-Based Health Risk Assessment and Its Application in the Neural Tube Defects Study of the Heshun Region, China. *Int. J. Geogr. Inf. Sci.* **2010**, *24*, 107–127. [CrossRef]
49. Zhai, Y.; Baran, P.K. Do Configurational Attributes Matter in Context of Urban Parks? Park Pathway Configurational Attributes and Senior Walking. *Landsc. Urban Plan.* **2016**, *148*, 188–202. [CrossRef]
50. Tsou, M.-H. Research Challenges and Opportunities in Mapping Social Media and Big Data. *Cartogr. Geogr. Inf. Sci.* **2015**, *42*, 70–74. [CrossRef]
51. Heikinheimo, V.; Tenkanen, H.; Bergroth, C.; Järv, O.; Hiippala, T.; Toivonen, T. Understanding the Use of Urban Green Spaces from User-Generated Geographic Information. *Landsc. Urban Plan.* **2020**, *201*, 103845. [CrossRef]
52. Li, Q.; Li, S.; Zhang, S.; Hu, J.; Hu, J. A Review of Text Corpus-Based Tourism Big Data Mining. *Appl. Sci.* **2019**, *9*, 3300. [CrossRef]
53. Padilla, J.J.; Kavak, H.; Lynch, C.J.; Gore, R.J.; Diallo, S.Y. Temporal and Spatiotemporal Investigation of Tourist Attraction Visit Sentiment on Twitter. *PLoS ONE* **2018**, *13*, e0198857. [CrossRef]
54. Corcoran, P.; Mooney, P.; Bertolotto, M. Analysing the Growth of OpenStreetMap Networks. *Spat. Stat.* **2013**, *3*, 21–32. [CrossRef]
55. Mashhadi, A.; Quattrone, G.; Capra, L. Putting Ubiquitous Crowd-Sourcing into Context. In Proceedings of the 2013 Conference on Computer Supported Cooperative Work, San Antonio, TX, USA, 23–27 February 2013; Association for Computing Machinery: New York, NY, USA, 2013; pp. 611–622.
56. Goodchild, M.F. Citizens as Sensors: The World of Volunteered Geography. *Geo. J.* **2007**, *69*, 211–221. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

buildings

MDPI

*Article*

# Enhancing Citizens' Perceived Restoration Potential of Green Facades through Specific Architectural Attributes

**Pegah Hajibeigi [1], Mahdieh Pazhouhanfar [1,*], Patrik Grahn [2] and Hasan Nazif [1]**

[1] Department of Architecture, Faculty of Engineering, Golestan University, Gorgan 49188-88369, Iran; pegahhajibeigi96@gmail.com (P.H.); h.nazif@gu.ac.ir (H.N.)
[2] Department of People and Society, Swedish University of Agricultural Sciences, Alnarp, P.O. Box 190, 234 56 Lomma, Sweden; patrik.grahn@slu.se
* Correspondence: m.pazhouhanfar@gmail.com or m.pazhouhanfar@gu.ac.ir

**Abstract:** Research on restorative environments has suggested green facades as a promising model for natural spaces in urban and densely populated areas. However, the impact of architectural design attributes of green building facades on perceived restoration potential is insufficiently researched. Therefore, this study aimed to investigate the relationship between architectural design attributes of green building facades and perceived restoration potential. A discrete choice experiment was used. First, seven architectural design attributes (Value, Symmetry, Material, Balcony, Variety, Configuration, and Shape) were identified based on the Content Identifying Method. In the next step, a sample of 204 participants randomly selected a block and evaluated the perceived restoration potential of six pairs of designed images of different green facade scenarios based on the seven architectural design attributes. The results showed that low diversity in greenery was associated with greater influence, and people chose asymmetric greenery more often. Horizontal and scattered greenery was preferred over vertical and concentrated greenery, which had no significant effect on perceived restoration potential. Stone and cement used in green facades were the most influential factors in perceived restoration potential. These findings can aid designers in designing the green facade of residential buildings to increase perceived restoration potential.

**Keywords:** biophilic design; mental health; restorative environment; mental fatigue; stress reduction; attention fatigue; attention restoration theory; calm and connection theory

**Citation:** Hajibeigi, P.; Pazhouhanfar, M.; Grahn, P.; Nazif, H. Enhancing Citizens' Perceived Restoration Potential of Green Facades through Specific Architectural Attributes. *Buildings* **2023**, *13*, 2356. https://doi.org/10.3390/buildings13092356

Academic Editors: Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Baojie He and Shi Cheng

Received: 6 August 2023
Revised: 8 September 2023
Accepted: 10 September 2023
Published: 16 September 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Urbanization has led to a significant increase in the number of people living in cities. While urban living offers many benefits, including access to employment opportunities, education, healthcare, and social services, it also comes with several challenges [1,2]. One of the most significant challenges is the lack of access to natural green spaces, which can have negative impacts on mental health and well-being. Urban residents who lack access to green spaces are more likely to experience stress, anxiety, and depression, which can lead to a range of physical and mental health problems [3].

Green facades, also known as living walls or vertical gardens, are an innovative solution to the problem of urban green space. These structures are made up of plants that grow vertically on the exterior walls of buildings, creating a green surface that can have positive effects on mental health and well-being by promoting restoration and reducing stress and mental fatigue [4,5]. The potential benefits of green facades in promoting mental health and well-being have led architects and urban planners to incorporate them into building designs [6]. By incorporating green facades into building designs, architects and urban planners can create buildings that not only provide shelter but also contribute to the physical and mental well-being of residents [7]. Our interest is based on architecture and environmental psychology and concerns how facades with vegetation are experienced

when viewed. In doing so, we want to include a broad palette of buildings found in urban environments today, which includes living walls and green facades, but also balconies with vegetation, planter boxes, etc. In the search for specific architectural attributes, we have thus broadened the range. In this article, green facades must therefore be understood in the broadest sense.

Of greatest interest in this context are those attributes in the architectural design of green facades can contribute to increasing residential buildings' perceived restoration potential. Despite the possible impact of green facades on the restorative potential of citizens, according to our assessment, there is a knowledge gap about the details of how green facades should be designed. The aim of this study is to investigate how different architectural designs of green facades can affect people's restoration potential. The objectives are partly to identify important attributes for green facades on residential buildings and partly to explore a model of the relationship between these attributes and their restorative potential.

The methodological considerations we made included several steps. To identify important attributes, a literature study was first carried out. The result of this could give us important clues about what to expect from the first experimental study: the Content Identification Method (CIM). The purpose of CIM was to identify groups of important architectural attributes. It is a reliable and frequently used method in architecture and environmental psychology, in which subjects judge a large selection of images. The result is interpreted based on the content of images and literature. The outcomes of this study will be used as stimuli in the second experimental study.

The second objective was to explore a model of the relationship between found architectural attributes and people's restoration potential. We needed to use a simple, valid and reliable self-assessment method regarding restorative potential. One such method that has long been used in environmental psychology research is Perceived Restorative Potential (PRP), which we chose to use in this study.

In order to accomplish the aim of the study, i.e., which architectural attributes in green facades have the greatest positive impact on perceived restoration potential, subjects need to be able to reliably make choices between different environments. The method we apply is the Discrete Choice Method (DCM), in which a sample of the study participants is presented with a set of images and asked to choose an option. It is a method that is reliable and is increasingly used in many different scientific fields.

## 2. Literature Review

### *2.1. Theories about the Restorative Impact of Green Environments*

Numerous studies confirm that natural environments positively affect people's psychological and physiological well-being [8,9]. Green spaces have been shown to have better restoration effects than urban built settings, supporting the role of natural elements in increasing the restoration of the urban landscape [9,10]. Due to people's lack of access to natural landscapes, parks and green spaces in cities have been introduced as restorative environments that enhance natural beauty and increase perceived restoration potential [11].

Attention Restoration Theory (ART) proposes that focusing on interesting and soft fascinating stimuli can alleviate cognitive inhibitory mechanisms, and sustained fascination can be achieved when the environment is perceived as coherent and extended [12,13]. Restorative settings, which include natural environments, offer opportunities for recovery of directed attention [13,14]. Attention recovery is characterized by four key components, including mystery, which refers to an environment's ability to inspire curiosity in individuals. Restoration is facilitated when individuals can engage in effortless, interest-driven involuntary attention while interacting with their environment [13]. Calm and Connection Theory [15] suggests that enriched natural environments in cities can lead to reduced stress, increased calmness, and vitality, making residents feel a greater sense of belonging and being at home in the city. In dense urban environments, enriched natural elements consisting of diversified, cultural elements can be experienced by all the senses, which increase the possibility of calmness and connection. In addition to sight, it is about hearing,

touch and the perception of movement, which softens the static impression of house bodies and creates vitality, curiosity and joy [16].

In summary, ART and CCT provide insights into the restorative benefits of natural environments and highlight the importance of soft, fascinating impressions from an enriched, diversified natural environment, which can enhance opportunities for recovery from directed attention fatigue and high levels of stress. Incorporating green spaces into urban landscapes using green facades can increase the restoration potential of cities and improve people's well-being.

### 2.2. Building-Integrated Vegetation

In recent decades, the increase in population and urbanization rates have led to a change in the pattern of human habitation. The shift from horizontal to vertical living has resulted in the construction of towers and skyscrapers, which have caused numerous problems. One of the major issues is the rise in environmental stressors and information overload [11,17–19]. Furthermore, the surrounding urban space has become a mechanical, and artificial environment, with artificial areas expanding at a faster rate than natural areas. As a result, traditional life has transformed into apartment living without any access to natural spaces. Additionally, the construction of buildings and the limitation of land for planting plants have deprived citizens of the opportunity to use natural spaces [20].

Integrating nature into high-rise buildings in densely populated areas with limited green space represents an innovative and sustainable solution for green infrastructure in cities [21]. Integrating buildings with vegetation has become a necessity in many metropolises worldwide, expanding the potential of vertical, horizontal, external and internal spaces to accommodate plants. This is particularly discussed in biophilic design [22]. As a result, several studies have suggested implementing vertical gardens and green facades to replace natural spaces in cities with limited greenery [23,24]. These restorative features can effectively reduce mental fatigue and stress levels, ultimately improving people's quality of urban life.

Aletta et al. [25] conducted a study on the benefits of vertical greening in urban areas, which promotes the coexistence of architecture and nature. The findings suggest that vertical gardens can enhance restoration and improve overall well-being in the urban environment, thereby increasing the quality of urban life. The researchers recommend the implementation of vertical gardens as a tool to increase green areas, alter the physical landscape, enhance architectural features, and promote restoration, particularly in dense urban spaces with limited green areas [26]. Similarly, Kozamernik et al. [27] conducted a study on the perception of green facades in urban environments and found that a greener urban environment is generally considered more pleasant, with most people believing that the vertical greenery system improves the quality of urban areas.

Previous studies have also demonstrated that green facades have a positive impact on human well-being and the environment. For instance, research has shown that green facades can improve air quality, reduce noise pollution, and regulate temperature [24]. Additionally, studies have found that incorporating vegetation into residential facades can enhance the aesthetic appeal of buildings and promote restoration, with green facades being perceived as more beautiful and restorative than those without [4]. However, despite these benefits, many residential areas still rely on potted plants on balconies or windowsills to create green facades due to economic, social, and geographical constraints.

The design of residential building facades plays a crucial role in shaping the urban environment and people's daily experiences [28]. Aesthetically pleasing facades contribute to the overall attractiveness of a city, while unappealing ones can have the opposite effect [29]. Given the diversity of ownership and personal taste in facade design, it is important to explore innovative solutions to improve the livability of urban spaces [30]. One promising approach is the use of green facades, which can provide numerous benefits for residents. To better understand the impact of green facades on restorative potential, it is

necessary to identify the key design attributes that are most effective in promoting positive residential perceptions.

### 2.3. People's Preferences for Architectural Features of Building Facades

In the literature review, it can be argued that although previous studies on restoration may not have directly addressed the identification of architectural features for green facades, information on environmental preferences can still provide valuable insights to inform this process. By analyzing individuals' preferences for green facades and their associated characteristics, the architectural components that contribute to these preferences can be identified. This can be used to extract relevant architectural features, although the specific focus of these studies was not on restoration.

The approach of using preference studies to identify architectural features can be considered valid and valuable. First, the use of this approach can result in the identification of important features that may have been overlooked in previous studies of restoration. Ultimately, incorporating these features into the restoration process can lead to more successful and sustainable restoration outcomes. Second, research studies show significant relationships between environmental preference and restorative qualities, indicating that environments with higher restorative qualities tend to be preferred by individuals [31].

Natural areas are often preferred over urban built environments due to their ability to regenerate and restore individuals [32]. Preference and choice are emotional responses to the surrounding environment, reflecting cognitive processes and perception. Understanding human perception of the environment requires an understanding of preference as an indicator of behavior and perception. Therefore, people's interaction with their surroundings is influenced by their preference for a particular place or landscape, which can create a sense of place for specific settings [33].

The literature review showed that specific attributes of greenery lead to more preferred and perceived beauty. *Greenery* has been identified as the most important factor in people's preferences, as *higher amounts of greenery* in streets have been associated with increased willingness to ride bicycles [34] and pay for residences on those streets [35]. The element "many trees" has the greatest effect on preferences, while the element "some trees" has a lesser effect [36]. Studies have also shown that the more available green spaces a residential area contains, the higher the preferences. Proximity, accessibility and quality can lead to the preference for green spaces varying within a residential block [37]. Moreover, higher vegetation cover has been found to increase the probability of restoration [11], and greater variation in perceived qualities of greenery has been shown to lead to more outdoor activities, higher neighborhood satisfaction, and better self-rated health among residents [38].

Research has shown that while *symmetry* is generally preferred in shapes and faces, natural landscapes without complete symmetry are preferred over those with two-way symmetry [39]. Additionally, the role of symmetry in the aesthetic judgment of residential buildings is influenced by people's expertise in architecture, with symmetrical facades corresponding to the taste of nonexperts [40]. However, a preference for symmetrical and complex stimuli may vary among nonartistic individuals [41]. Nevertheless, most studies suggest that visual qualities such as symmetry are influential in determining visual preferences for architectural views.

The relationship between *architectural elements* and visual preferences has been studied extensively. Researchers have found that the *diversity of architectural elements* in facades correlates positively with increased preference for windows. Additionally, the *variety of plants* in a residential area can also impact participants' preferences [36,42]. van Dongen et al. (2019) discovered that horizontal greenery had a greater impact on residential streets than vertical greenery, and concentric configurations were generally less preferred [43]. Chen (2011) listed various spatial arrangements and noted that each creates a distinct sense of place. For instance, a *concentrated organization* with a tree in the center can serve as a

dominant space, while a linear organization encourages movement in a straight line and offers a powerful perspective [44].

Furthermore, the choice of *materials* for green facades can also affect people's preferences. Research has indicated that architects tend to prefer brick and cement facades, while nonarchitects prefer stone facades [45]. Materials not only contribute to the identity of the facade but also play a crucial role in creating visual elements that evoke historical or modern perspectives. Therefore, designers should carefully consider the materials used in creating green facades to ensure that they enhance the aesthetic appeal of the urban environment and meet people's preferences [46].

Recent research highlights the potential of terraces and *balconies* as highly desirable features of apartment buildings in subtropical cities like Australia. Private outdoor spaces, such as balconies, contribute significantly to residents' perception of livability, offering additional living space for a range of daily indoor activities [47]. With the reduction of vegetation in inner-city areas and increasing densification, these spaces are becoming increasingly important for restoration with appropriate greenery [23]. The absence of a balcony or garden can directly impact life satisfaction, leading to a desire to move [2].

## 3. Methods

### *3.1. The Content Identifying Method*

The Content Identifying Method (CIM) was developed by Stephen Kaplan and colleagues [48,49]. It involves having a selection of study participants' rating images to obtain information about people's preferences for features and qualities in the landscape. In the procedure, study participants are asked to rate a series of landscape scenes based on their *preferences* for each scene. After the subjects have rated the images, the data are processed with exploratory factor analysis. The aim of a factor analysis is to reveal underlying phenomena that explain relationships between several outcomes, in our case, architectural attributes. We used SPSS exploratory factor analysis, principal component analysis with varimax orthogonal rotation, where each factor has an eigenvalue greater than or equal to one [50].

The result of the analysis will be a number of groups of images. Each group of images has been judged similarly by the subjects, where some essential attribute or quality of the images has brought them together into the group. The higher the factor loading of an image, the more clearly the essential attribute appears in that image. Images with a factor loading of 0.40 and higher are included in each group. These groups of images are analyzed and interpreted based on their content and spatial qualities by researchers. In our case, the interpretation was based partly from our literature review and partly from acquired knowledge as architects, to reveal people's responses to input stimuli.

CIM is based on people's preferences and is considered reliable, because preference decisions are easy for people to make because people make many preference decisions for their daily routines. That is, people's reactions to environments are not solely based on immediate feelings but also on perceptual–emotional categories that are somewhat general. However, studies have shown that familiarity with a place can impact environmental priorities [51,52]. Additionally, research has found that the preferences of residents and visitors to a place may differ. Therefore, when conducting environmental preference studies including pictures, it is important to consider the familiarity of participants with the stimuli presented [53].

The steps involved in the CIM include questionnaire design, involving the scene collection procedure, the scene selection procedure, and the scene presentation procedure. Data collection was performed using a photo-questionnaire. A photo questionnaire is an excellent approach to show the natural environment [54–57]. In order to gauge people's preferences for green facades on residential buildings, a collection of images depicting various types of green facades was obtained through a stratified selection process. As all the images were sourced from virtual space, there was a wide range of designs and styles represented in the green views. This allowed for a comprehensive assessment of

people's preferences for different types of green facades, and provided valuable insights into the most popular styles and designs. Overall, this study highlights the importance of incorporating greenery into urban environments, and the potential benefits that can be derived from doing so.

More than 200 images of residential buildings of green facade were collected, and 100 images taken from the front view were ultimately selected. These photos were grouped based on their similarity, and a researcher supervision committee was responsible for this process to reduce bias and increase the questionnaire's validity. After this process, 32 images were selected for use in the survey questionnaire. After reaching this set of 32 images, four additional images at the beginning and another four at the end of the image sequence were added. The purpose of the first four images was to familiarize participants with the image rating method, while the final four images helped prevent participants from predicting subsequent images [55]. Participants were asked to rate their preferences using a scale ranging from one to five (1 = I do not like this scene, to 5 = I like this scene very much).

SPSS software (Version 26) was utilized in this study to analyze questionnaire data. Descriptive analysis was employed to gather demographic information about the participants. Based on the preferences of the students, a mean analysis was conducted, and the landscape patterns were ranked accordingly. The scenes were categorized into groups to reduce the amount of information based on these patterns. To classify scenes that were similar to one another based on loading factor, exploratory factor analysis was carried out using principal component analysis, with an internal consistency threshold of above 0.7 recommended. This method has been used in many research studies [57–60].

Study Participants

The participants in the CIM study had different backgrounds in terms of gender, age and education level. There were 39 males (39%) and 61 females (61%). Participants were in the age group of 15–20 years (n = 18, 18%), followed by 21–25 years (n = 38, 38%), 26–30 years (n = 18, 18%) and above 30 (n = 26, 26%). The majority of participants were between 21 and 25 years old. Participants' education level was as follows: high school (n = 7, 7%), diploma (n = 25, 25%), associate degree (n = 18, 18%), Bachelor of Science (n = 38, 38%), Master of Science (n = 9, 9%) and Doctorate (n = 3, 3%) (Table 1).

**Table 1.** Sample Classification for CIM study.

| | Classification | Frequency Percentage (%) |
|---|---|---|
| Gender | Male | 39 |
| | Female | 61 |
| Age | 15–20 years old | 18 |
| | 21–25 years old | 38 |
| | 26–30 years old | 18 |
| | Over 30 years old | 26 |
| Education | High school | 7 |
| | Diploma | 25 |
| | Associate degree | 18 |
| | Bachelor of Science | 38 |
| | Master of Science | 9 |
| | Doctorate | 3 |

### *3.2. The Perceived Restorative Potential*

One overarching object of the study was to measure overall perceived restorativeness; that is, how much a study participant would agree that a certain place would be great to take a break in, restoring from high stress levels and mental fatigue. A valid and reliable single measure of overall perceived restorative potential was developed by Herzog et al. [14], who asked students to recall a time when sustained effort led to fatigue, and then rate how good different locations would be for taking a break and restoring the ability to work effectively

on a project. Since then, the Perceived Restorative Potential (PRP) measure, has come to be used increasingly frequently, and refers to restoration from both directed attention fatigue and high stress levels [61].

In this study, participants were first instructed to imagine walking home alone in the afternoon after a mentally taxing day at work. Next, they chose the image they thought would be most restorative. Perceived restorative potential was measured by instructing subjects to do the following: "Remember a time when you felt overwhelmed, stressed, tired, and anxious. Reflect on how you felt at that moment and put yourself in that mindset. Continue to reflect on this mindset when you look at the pictures and imagine yourself in each setting. For each of the pictures presented, rate the degree to which you think it would be a good place for you to take a break and make you feel less stressed and anxious to be in that environment."

### *3.3. The Discrete Choice Method*

To investigate the relationship between the green facade of a residential building and PRP, a discrete choice experiment was conducted. The Discrete Choice Method (DCM) is a popular approach for studying people's preferences in a variety of fields [62], including environmental economics, tourism, marketing, transportation, and health [63–67]. In our case, we did not ask for the subjects' preferences, but, instead, asked for their estimate of the Perceived Restorative Potential (PRP) as described above.

In this method, respondents are presented with a set of choices and asked to select one option [68]. Each option in the set represents a different combination of attributes that describes a desired product or service. These attributes are assigned different levels, allowing researchers to examine how changes in the attributes affect people's choices. An attribute can be, for example, a tree in the image. The level can then be 1 = there are trees, or 0 = there are no trees. The levels can also be missing = 0, few = 1 and many = 2. One of the main steps in this method is to determine the attributes and their levels. In this study, we used the Content identifying method (CIM) for this purpose. A full factorial design takes into account all possible combinations of attributes and levels. A full factory design is appropriate when there are only a few components to consider. However, when there are many components to consider, and when many possible combinations probably have little effect, a calculation of a subset of important combinations, a so-called fractional factorial design available in the ADX Interface SAS/QC, allows an estimation of the main effects, giving a better opportunity to focus on them [69,70].

The images used in this experiment were generated using Photoshop and SketchUp software (SAS Version 9.2), in order to include the attributes and levels that CIM resulted in. The validity of using images instead of real environments is high, and research show no significant differences between preference ratings of images versus actual environments [53,54].

#### 3.3.1. Questionnaire Design

We used online questionnaire for data collection. The questionnaire was divided into two parts: the first part focused on gathering demographic information such as gender, age, marital status, education, and occupation. The second part utilized a visual discrete choice experiment. Respondents were randomly assigned to a block of 6 sets, each with three options: option 1, option 2, and none. Participants were presented with different scenarios and asked to select the option that maximized their utility based on their perceived restorative potential, PRP. The desirability of each option was determined by its attributes, which were presented visually rather than textually. Participants were instructed to imagine walking home alone in the afternoon after a mentally taxing day at work, and to choose the image that they believed would be most restorative. The questionnaire consisted of six series of questions, each containing two suggested options and a "none" option to prevent respondents from feeling forced to choose an option and to reduce the possibility of exaggerated preferences. Each respondent made six choices in total.

3.3.2. Study Participants

The participants in this study had diverse backgrounds in terms of gender, age, education level, marital status, and occupation. There were 60 male participants, accounting for 29% of the total sample, and 144 female participants, accounting for 71% of the total sample. They were divided into different age groups: 8% (16 participants) were between 15 and 20 years old, 33% (68 participants) were between 21 and 25 years old, 23% (47 participants) were between 26 and 30 years old, and 36% (73 participants) were 30 years old or older. Fifty-one percent (110 participants) of the participants were single, and 49% (94 participants) were married. Participants' education level was as follows: undergraduate (n = 56, 26.5%), Bachelor of Science (n = 99, 48.5%), Master of Science (n = 39, 19.5%) and Doctorate (n = 10, 5%) (Table 2).

**Table 2.** Sample Classification for DCM study.

| | **Classification** | **Frequency Percentage (%)** |
|---|---|---|
| Gender | Male | 29 |
| | Female | 71 |
| Age | 15–20 years old | 8 |
| | 21–25 years old | 33 |
| | 26–30 years old | 23 |
| | Over 30 years old | 36 |
| Relevance | Single | 51 |
| | Married | 49 |
| Education | Undergraduate | 26.5 |
| | Bachelor of Science | 48.5 |
| | Master of Science | 19.5 |
| | Doctorate | 10.5 |

3.3.3. Data Analysis

According to the data analysis, the multinomial logit (MNL) model was used, which is suitable for discrete choice tests. The multinomial logit model is called multinomial choice as one of the discontinuous selection models. The essential feature of the multinomial logit model is that the assumptions related to the probability distribution of error sentences suggest the hypothesis of independence of unrelated options. In other words, the relative choice of two options depends only on their usefulness. First, the necessary data for the parameters in the mathematical relationships of this model should be generated to use the logit model and define the significance of variables after solving the model. The probability and type of influence (positive or negative) of each of the significant variables on the dependent variable (revival) was obtained.

More choices are considered in the multinomial logit model, which is defined with the assumption that the error sentences are independent of each other and have Gamble distribution (Equation (1)).

$$P_{in} = \Pr(y_n = i) = \frac{\exp(v(x_{in}\,\beta)}{\sum_{i=1}^{i} \exp(v(x_{in}\,\beta)} \quad (1)$$

According to the researcher, the probability that a person chooses an option is between zero and one (zero to 100%). The outcome of the decision is represented by y for each choice set. The probability of selecting an option tends to be one as the observed utility increases, and zero if the utility decreases [71].

$$\underset{v\to\infty}{\mathrm{Lim}} \Pr(y = 1) = 1 \quad (2)$$

$$\lim_{v\to\infty} \Pr(y = 1) = 0 \quad (3)$$

One level (level 1) is removed from each variable. Other levels are defined relative to the removed level to analyze the results because the information is entered as 0 and 1 for each feature.

A Dummy coding method was used for this analysis. For example, 1 = no similarity, 2 = similarity; 1 = centralized, 2 = decentralized; 1 = brick material, 2 = cement material, 3 = stone material; 1 = low volume, 2 = medium volume, 3 = high volume; 1 = horizontal shape, 2 = vertical shape; 1 = diversity, 2 = no diversity; 1 = absence of a balcony, 2 = presence of a balcony.

### *3.4. Main Survey Process*

Due to the impact of COVID-19, an online survey questionnaire was used to collect data, which was created and administered through the Porsline.ir website. To encourage participation, nonmonetary incentives were offered, as is common in web-based surveys. The questionnaire was designed using an online platform that allows for easy creation, editing, and promotion of surveys. The survey was widely distributed through social media, including WhatsApp, Telegram, and Instagram, which have been used successfully in previous studies, allowing for maximum reach with minimal time and cost. CIM and DCM questionnaires were uploaded to Porsline Website and a questionnaire link was generated and sent to people.

## 4. Results

### *4.1. The Content Identifying Method*

#### 4.1.1. Participants' Preferences for Green Facades

Figure 1 shows that scene 2 (M = 28.4, S.D. = 0.80) was the most preferred scene according to the participants followed by scene 26 (M = 4.15, S.D. = 0.71), scene 5 (M = 4.05, S.D. = 1.02), scene 11 (M = 4.03, S.D. = 0.95) and scene 21 (M = 4.02, S.D. = 0.84). The scenes illustrated the medium value and liner greenery. The majority of these scenes have horizontal greenery (scenes 2, 11 and 21), symmetry (scenes 2, 26 and 21) and four scenes (scenes 2, 26, 5 and 21) have stone and cement material. Scene 2 has the highest mean, so facades with medium value, liner, symmetry and horizontal greenery and stone and cement material have the most preferences.

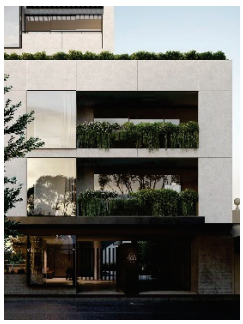
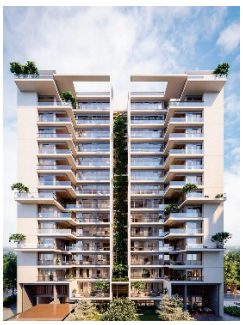
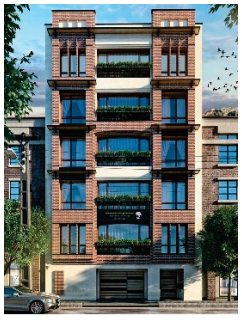
| Scene 2 | Scene 26 | Scene 5 | Scene 11 | Scene 21 |
|---|---|---|---|---|
|  |  | |  | |
| M = 4.28, S.D. = 0.8 | M = 4.15, S.D. = 0.71 | M = 4.05, S.D. = 1.02 | M = 4.03, S.D. = 0.95 | M = 4.02, S.D. = 0.84 |

**Figure 1.** Five most-preferred scenes for the greenery on façades.

Figure 2 shows scene 18 (M 1/4 1.59, S.D. 1/4 0.79) as the least preferred scene of green facades followed by scene 17 (M 1/4 1.63, S.D. 1/4 0.83), scene 25 (M 1/4 0.67, S.D. 1/4 1.74), scene 1 (M 1/4 2.01, S.D. 1/4 1.11) and scene 15 (M 1/4 2.15, S.D. 1/4 1.01). These scenes have a low value and scattered greenery. The majority of these scenes have no symmetry (scene 25, 1 and 15) and no greenery on both sides (scenes 18, 17 and 1). Thus, high value, greenery on both sides, symmetry and horizontal greenery are important for facades.

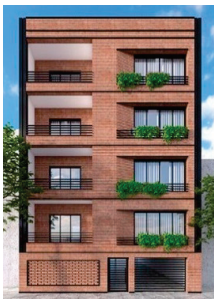
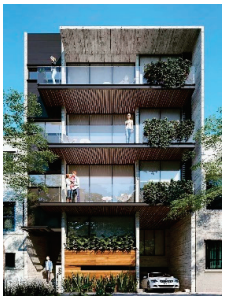
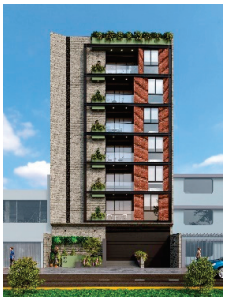
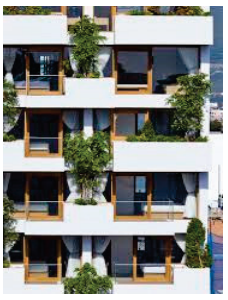
| Scene 18 | Scene 17 | Scene 25 | Scene 1 | Scene 15 |
|---|---|---|---|---|
|  |  | |  |  |
| M = 1.59, S.D. = 0.79 | M = 1.63, S.D. = 0.83 | M = 1.74, S.D. = 0.67 | M = 2.01, S.D. = 1.11 | M = 2.15, S.D. = 1.01 |

**Figure 2.** Five least-preferred scenes for the greenery on facades.

#### 4.1.2. Factor Analysis Output into Green Facades Scenes

The first factor (high value of greenery) had the highest mean (3.87), explained variance of 7.46 and reliability coefficient of 0.93 with three scenes of a high amount of greenery on facades. The second factor (stone and cement material) had a mean of 3.74, 7.16 explained variance and 0.63 as a reliability coefficient with four scenes of greenery on facades. The third factor (one-sided) with a mean of 2.45, an explained variance of 5.8, and 0.45 as a reliability coefficient, contained four scenes of green facades (Table 3).

**Table 3.** Factor scenes based on factor analysis.

| | Scene | Mean | S.D. | Factor Loading | Variance Explained |
|---|---|---|---|---|---|
| High value | **-** | **3.87** | **0.93** | **-** | **7.46** |
| | Scene 5 | 4.05 | 1.02 | 0.73 | |
| | Scene 9 | 3.7 | 1.2 | 0.68 | |
| | Scene 16 | 3.8 | 1.16 | 0.43 | |
| Stone and cement material | **-** | **3.75** | **0.63** | **-** | **7.16** |
| | Scene 24 | 2.88 | 1.33 | 0.59 | |
| | Scene 2 | 4.28 | 0.8 | 0.55 | |
| | Scene 21 | 4.02 | 0.84 | 0.43 | |
| | Scene 13 | 3.81 | 1.16 | 0.41 | |
| One side | **-** | **2.45** | **0.45** | **-** | **5.8** |
| | Scene 23 | 2.3 | 0.83 | 0.65 | |
| | Scene 27 | 2.36 | 0.65 | 0.57 | |
| | Scene 10 | 2.22 | 1.31 | 0.47 | |
| | Scene 18 | 1.59 | 0.79 | 0.42 | |
| Concentrated | **-** | **2.74** | **0.4** | **-** | **5.73** |
| | Scene 12 | 3.08 | 0.72 | 0.59 | |
| | Scene 19 | 4.01 | 1.05 | 0.53 | |
| | Scene 25 | 1.74 | 0.67 | 0.53 | |
| | Scene 15 | 2.15 | 1.01 | 0.41 | |
| | Scene 31 | 3.6 | 1.08 | 0.42 | |
| Symmetrical | **-** | **3.75** | **0.68** | **-** | **5.48** |
| | Scene 14 | 3.8 | 1.1 | 0.63 | |
| | Scene 6 | 3.75 | 1.38 | 0.6 | |
| | Scene 7 | 3.71 | 1.2 | 0.55 | |
| Greenery in the balcony | **-** | **3.14** | **0.56** | **-** | **5.42** |
| | Scene 20 | 2.93 | 0.98 | 0.57 | |
| | Scene 4 | 3.01 | 0.75 | 0.56 | |
| | Scene 32 | 3.49 | 0.81 | 0.56 | |
| Repetition | **-** | **3.15** | **0.58** | **-** | **5.00** |
| | Scene 3 | 3.15 | 0.77 | 0.6 | |
| | Scene 1 | 2.01 | 1.11 | 0.49 | |
| | Scene 22 | 3.85 | 1.07 | 0.48 | |
| Vertical | **-** | **2.94** | **0.49** | **-** | **4.62** |
| | Scene 26 | 4.15 | 0.71 | 0.7 | |
| | Scene 29 | 3.06 | 1.19 | 0.64 | |
| | Scene 17 | 1.63 | 0.83 | 0.51 | |

The fourth factor, 'concentrated', with a mean of 2.74, explained variance of 5.73, and 0.4 as a reliability coefficient included five scenes of greenery on facades. The fifth factor, 'symmetry', with a mean of 3.75, explained variance of 5.48, and 0.68 as a reliability coefficient, included three scenes of greenery on facades. The sixth factor, 'greenery in the balcony', with a mean of 3.14, explained a variance of 5.42, and 0.56 as a reliability coefficient, included three scenes of greenery on facades. The seventh factor, 'repetition', with a mean of 3.15, explained a variance of 5.00, and 0.58 as a reliability coefficient included three scenes of green facades. Finally, the eighth factor, 'vertical' with a mean of 2.94, 4.62 as explained variance and 0.49 as a reliability coefficient, included three scenes of green facades (Table 3).

4.1.3. Preference for the 'factors' of the Green Facade

'High value of greenery' has the highest mean (M 1/4 3.87, S.D. 1/4 0.93), followed by 'symmetry' (M 1/4 3.75, S.D. 1/4 0.68), 'stone and cement material' (M 1/4 3.74, S.D. 1/4 0.63), 'repetition' (M1/4 3.15, S.D. 1/4 0.58), 'greenery in the balcony' (M1/4 3.14, S.D. 1/4 0.56), 'vertical' (M1/4 2.94, S.D. 1/4 0.49), 'concentrated' (M1/4 2.74, S.D. 1/4 0.4) and 'one-side' (M1/4 2.45, S.D. 1/4 0.45). High value of greenery has the highest mean and all scenes in this factor show a high and medium value of greenery. Greenery on one side has the lowest mean and all the scenes include greenery on one side of the facade.

4.1.4. Content Analysis of Factors for the Green Façade

Figure 3 shows the architectural design attributes in the facades of the buildings, which includes 28 scenes in eight facade factors. The first factor (high value of greenery) includes three scenes, which have no disturbances and the main feature is the high amount of greenery in the view. The second factor (stone and cement facade material) includes four scenes, because stone and cement materials are used in addition to greenery in the facade. The third factor (one-sided greenery) includes four scenes. In these pictures, greenery is on one side of the view, yet greenery is not visible on the other side. The fourth factor (concentrated greenery) includes five scenes in which greenery is placed in specific points of the view and no linear or integrated pattern can be seen. The fifth factor (symmetrical greenery) includes three scenes, which have relative greenery with a horizontal or vertical line of reference. The sixth factor (greenery in the balcony) consists of three scenes, in which the greenery is in the door of the balcony and less greenery is seen in front of the window. The seventh factor (repetition in greenery) consists of three scenes, in which repeated greenery has a specific pattern without variation. The eighth factor (vertical greenery) includes three scenes, in which greenery is seen in as vertical lines or next to each other on different floors.

The content analysis results of these senses showed that people prefer the green view with a large or medium amount of greenery. Furthermore, facades with repetition in greenery were associated with a higher preference, and the preferred material used next to the greenery in the green facade was stone and cement. The balcony on the facade and the placement of greenery on the balcony of the building is preferred. Concentrated greenery is preferred on the facade. The greenery of a building is better to be designed horizontally, and people seem to prefer something more than greenness that is visible vertically.

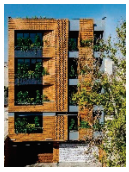
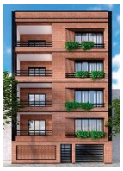
| High value | Stone and cement material | One side | Concentrated | Symmetrical | Greenery in the Balcony | Repetition | Vertical |
|---|---|---|---|---|---|---|---|
| Scene 5 | Scene 24 | Scene 23 | Scene 12 | Scene 14 | Scene 20 | Scene 3 | Scene 26 |
| | | | | | | | |
| M = 4.05 load.fac = 0.73 | M = 2.88 load.fac = 0.59 | M = 2.3 load.fac = 0.65 | M = 3.08 load.fac = 0.59 | M = 3.8 load.fac = 0.63 | M = 2.93 load.fac = 0.57 | M = 3.15 load.fac = 0.6 | M = 4.15 load.fac = 0.7 |
| Scene 9 | Scene 2 | Scene 27 | Scene 19 | Scene 6 | Scene 4 | Scene 1 | Scene 29 |
| | | | | | | | |
| M = 3.7 load.fac = 0.68 | M = 4.28 load.fac = 0.55 | M = 2.36 load.fac= 0.57 | M = 4.01 load.fac = 0.53 | M = 3.75 load.fac = 0.60 | M = 3.01 load.fac = 0.56 | M = 2.01 load.fac = 0.49 | M = 3.06 load.fac = 0.64 |
| Scene 16 | Scene 21 | Scene 10 | Scene 25 | Scene 7 | Scene 32 | Scene 22 | Scene 17 |
| | |  | | | | | |
| M = 3.8 load.fac = 0.43 | M = 4.02 load.fac = 0.43 | M = 2.22 load.fac = 0.47 | M = 1.74 load.fac = 0.53 | M = 3.71 load.fac = 0.55 | M = 3.49 load.fac = 0.56 | M = 3.85 load.fac = 0.48 | M = 1.63 load.fac = 0.51 |
| | Scene 13 | Scene 18 | Scene 15 | | | | |
| | |  | | | | | |
| | M = 3.81 load.fac = 0.41 | M =1.59 load.fac = 0.42 | M = 2.15 load.fac = 0.41 | | | | |
| | | | Scene 31 | | | | |
| | | | | | | | |
| | | | M = 3.6 load.fac = 0.42 | | | | |

**Figure 3.** Facade scenes based on factor analysis.

Based on the literature review and result of CIM, seven variables were selected for use in DCM (Table 4). The CIM method was used based on the research background, which emphasized the importance of high value, a large amount of greenery and symmetrical greenery of the facade. Furthermore, people prefer green facades with stone and cement materials and the presence of greenery on the balcony, while facades with concentrated greenery are the least preferred. Moreover, a green facade of a building is better to be designed horizontally, and people prefer something more than greenery that is visible vertically. Therefore, according to the obtained results, the proposed theoretical model is presented (Figure 4).

**Table 4.** Architectural design attributes used in DCM on green facades.

| Attributes | Levels | References |
|---|---|---|
| Value | Low, Medium, High | [14,34–37,72–74] |
| Symmetry | Exist, Non exist | [39,40,46] |
| Material | Brick, Cement, Stone | [46,47] |
| Balcony | Exist, Non exist | [2,21,47] |
| Variety | Exist, Non exist | [75,76] |
| Configuration | Concentrated, Scattered | [43,44] |
| Shape | Vertical, Horizontal | [43,44] |

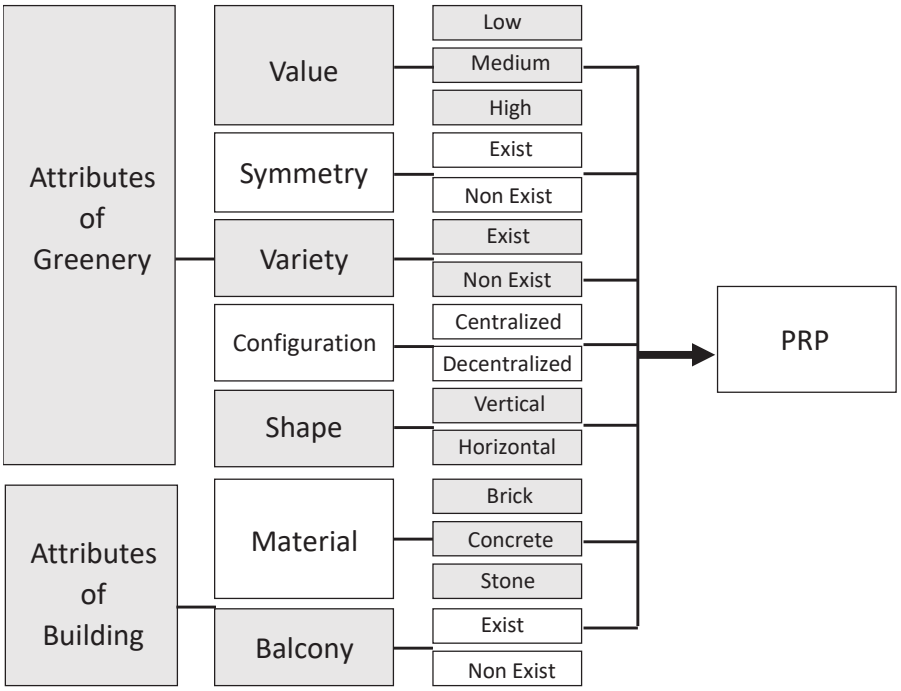



**Figure 4.** Theoretical model.

According to the results of the literature review and CIM, the following model was suggested:

*4.2. Discrete Choice Method*

In the Discrete Choice Method, seven attributes where utilized as independent variables, as outlined in Table 4. To ensure optimal results from the data, the test design is critical [77], and a complete factorial design would require all possible combinations of levels and components ($3 \times 2 \times 3 \times 2 \times 2 \times 2 \times 2 = 228$). However, due to the complexity of the variables and levels involved, a fractional factorial design was employed using SAS 9.2 SAS/QC ADX Interface software to reduce the number of scenarios to 72 in six blocks, each comprising six sets with three options (option one, option two, and none). Images were generated using Photoshop and SketchUp software for each option, with the base view selected from the top five views in the CIM test. The design was produced according to the results of SAS 9.2 software, with the building facade attributes fixed except for the variables used in the design. Figure 5 provides an example of a choice task with seven variables in a discrete choice experiment.

| set | alternative | value | symmetry | material | balcony | variety | configuration | shape |
|---|---|---|---|---|---|---|---|---|
| 1 | Picture1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 |
| | Picture2 | 3 | 1 | 1 | 1 | 2 | 2 | 2 |

**Figure 5.** Overview of different levels for two images: (**left image**) medium value, symmetrical, cement material, presence of balcony, variability, concentrated and horizontal greenery. (**right image**) high value, no symmetrical, brick material, absence of balcony, no variability, scattered and vertical greenery.

An MNL was run the investigate the relationship between attributes of design green facades and PRP. The results of Table 5 show that all the attributes significantly affect the utility of green facades except for materials and architectural style (traditional). A positive sign of the coefficients throughout the model means that a higher value of the variable increases the probability of choosing a visual attribute compared to the reference level. Based on the results in Table 5 regarding greenery attributes, the respondents preferred asymmetry over symmetry in green facades ($\beta = 0.75$, $p < 0.00$). In terms of shape attributes, due to the negative effect coefficients, participants preferred vertical over horizontal green facades ($\beta = -0.26$, $p < 0.003$). A variety of greenery was also found to be significant ($\beta = -0.48$, $p < 0.00$). That is, the more variety, the lower the perceived restorative potential. The result of the value attribute showed that participants preferred high value over low value ($\beta = 0.63$, $p < 0.00$); however a medium effect value of variability in greenery was also found to be significant ($\beta = 0.224$, $p < 0.051$). In addition, they also preferred scattered greenery on the facades over concentrated greenery on the facades ($\beta = 0.559$, $p < 0.0001$). Regarding facade attributes, stone and cement material were preferred over greenery attributes ($\beta$ Stone = 0.995, $\beta$ cement = 1.792, $p < 0.00$). The result for the balcony was not found to be significant at $p < 0.05$. Table 5 shows that the stone and cement material for facades were preferred over greenery attributes. Stone had the most positive influence on preference, followed by cement. Among greenery attributes, no symmetry and high value had the most effect, followed by no variation in greenery. Vertical, medium value and scattered had the lowest values (Figure 6).

**Table 5.** Relationship between attributes of design green facades and PRP.

| | Attributes | Base Level | Coef. | Std. Err. | z | *p* | [95% Conf.-Interval] | |
|---|---|---|---|---|---|---|---|---|
| Greenery | **Symmetry** | | | | | | | |
| | No choice | | 0.237 | 0.171 | 1.39 | 0.165 | −0.098 | 0.574 |
| | No Exist | Exist | 0.747 | 0.091 | 8.17 | 0.00 | 0.568 | 0.927 |
| | **Shape** | | | | | | | |
| | Vertical | Horizontal | -0.262 | 0.089 | 2.92 | 0.003 | −0.438 | −0.086 |
| | **Value** | | | | | | | |
| | Medium | Low | 0.224 | 0.115 | 1.95 | 0.051 | −0.001 | 0.45 |
| | High | | 0.633 | 0.11 | 5.75 | 0.00 | 0.417 | 0.85 |
| | **Variety** | | | | | | | |
| | Exist | No exist | 0.483 | 0.9 | 5.32 | 0.00 | 0.661 | 0.304 |
| | **Position** | | | | | | | |
| | Scattered | Concentrated | 0.188 | 0.089 | 2.1 | 0.036 | 0.0125 | 0.365 |
| Facade | **Material** | | | | | | | |
| | cement | Brick | 0.995 | 0.115 | 8.63 | 0.00 | 0.769 | 1.222 |
| | Stone | | 1.792 | 0.114 | 15.68 | 0.00 | 1.568 | 2.017 |
| | **Balcony** | | | | | | | |
| | presence | absence | 0.17 | 0.9 | 1.88 | 0.06 | −0.007 | 0.348 |
| | **Model specification** | | | | | | | |

Number of obs = 3672, LR chi2 (10) = 633.25, Prob > chi2 = 0.000, Pseudo $R^2$ = 0.1355, Log likelihood = −2020.6572.

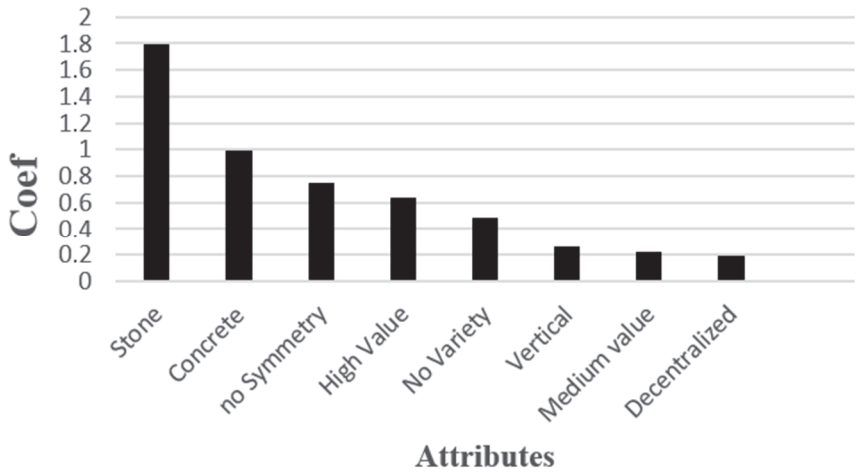



**Figure 6.** Preference for architectural design attributes of green façades.

## 5. Discussion

This study aimed to investigate which architectural attributes of green facades improve people's perceived restorative potential. Knowledge of this can be used by practitioners in architecture and urban planning to increase people's opportunities for recovery from high stress levels and attention fatigue as well as promote people's mental well-being in urban landscapes.

First, the results show that *a medium to high amount of greenery* on facades can improve people's perceived restorative potential. The amount of greenery is the most critical variable in people's preferences, and this is in line with previous studies. There are several examples, such as higher levels of greenery in streets lead to an increased preference for cycling [34] and willingness to pay for residences on those streets [35]. Furthermore, the element "many trees" has a more significant effect than "some trees" on preferences [34,36] Similarly, Zhang et al. (2017) found preferences for greenery in different parts of a residential block, with a greater preference for a higher value of greenery [37]. In addition, studies show that greenery in the workplace, for example greenery visible through windows, significantly affects workers' recovery potential from stress levels [73]. A study also revealed that a

high value of greenery on the facade contributes to higher PRP [14]. Research has shown that increased vegetation has a more restorative effect, and people generally prefer natural environments to urban settings, highlighting the need for nature in human lives [74].

Furthermore, the study found that *asymmetric greenery* positively affects people's perceived restorative potential. This finding was unexpected. While studies have shown a general preference for symmetry in shapes and faces, natural images without complete symmetry are preferred for landscapes [39]. Symmetrical greenery may be perceived as unnatural, and according to our results, does not positively affect perceived restoration. The result may also be influenced by education and background, where artists and architects may have different preferences than nonexperts [40]. The aesthetic experience of building facades is influenced by people's expertise, with symmetrical facades corresponding to the taste of nonexperts. Asymmetry may not necessarily lead to equal preferences for expert and nonexpert groups in eye movements in face images [40], and nonartistic individuals may find symmetrical and complex stimuli more beautiful [46]. Despite this, most studies have shown that visual qualities such as symmetry are influential in the visual preferences of architectural views. While symmetry may not necessarily enhance the beauty of natural landscapes, it can be a positive quality in artificial landscapes as they are treated like patterns or objects [39].

A third finding that was initially unexpected was that a *low variation* in greenery led to a high perceived restorative potential. However, research shows that stressed and tired people like to visit areas with low diversity in order to recover. The more stressed and tired a person is, the more evident this becomes [75]. Studies have also shown that complex and varied urban environments are tiring, while a less complex and varied green structure in cities leads to cognitive recovery [76]. In that context, it is interesting that our subjects rate green walls against a background of *stone and cement* as more restorative compared to if the greenery instead has a background of a complex and varied brick wall. According to some studies on materials, *stone materials and white cement* have the most significant effect on green facades. Consistent with Ghomeshi et al. (2013), architects preferred brick and cement facades more, and nonarchitects preferred stone façades [45]. Some studies have stated that materials can show the identity of the façade. However, others have considered them one of the most important visual elements that depict images and recall history or perspectives, including materials, especially modern materials, for shaping people's appreciation of beauty [46].

Fourth, our results showed that *horizontal greenery* on facades, as well as *scattered greenery*, has a clearly greater positive effect on people's perceived restorative potential than vertical greenery and more concentrated greenery on facades. In line with results of the study by Dongen et al. (2019), vertical greenery has a more negligible impact on residential streets than horizontal greenery, and low preference values were found for all designs with concentric configurations [43]. This study showed that horizontal and scattered greenery have a positive effect and significant coefficients on revitalization. In other words, linear and scattered greenery on facades encourage people to go straight and offer a powerful perspective [44]. Hypothetically, scattered greenery on facades is also perceived to be greener than concentrated greenery.

Another important variable that affects people's preferences and PRP when visiting green facades is the presence of balconies. Researchers have found that private outdoor spaces, such as terraces and balconies, are highly desirable features of apartment buildings, as they contribute to residents' perception of livability and provide additional living space for daily activities [47]. Moreover, these outdoor spaces can also be potential contributors to PRP through the introduction of appropriate greenery, especially in inner-city areas with reduced vegetation and densification [21]. The lack of a balcony or garden has been directly linked to decreased life satisfaction and may stimulate the desire to move [2]. However, the presence of a balcony was not significantly associated with PRP in this study ($p = 0.06$).

Some of our results were unexpected, where the qualities of green facades in terms of aesthetic preference and support for recovery from high stress levels and attention fatigue

differed markedly. However, several studies show that high preferences for certain qualities in green areas by the general public and high restoration potential do not correspond. This applies, for example, to species richness and variety as well as social meeting places [78,79].

## 6. Conclusions

It is important to recognize the significance of nature and visual landscapes, as well as the positive impact of green facades, on people's health. Identifying the elements of green facades that contribute to PRP is a crucial step towards improving the mental well-being of individuals in urban environments. Urban naturalization and enhancing green facades should be prioritized. This study highlights how the design of residential building green facades can impact the mental restoration of citizens. A green facade with a high amount of greenery, asymmetric greenery, stone and cement materials, horizontal greenery, scattered greenery, and a low level of variation in greenery attributes is effective in promoting mental restoration among citizens. Several of these results are somewhat unexpected, but must be considered from the perspective of being able to support recovery from high stress levels and attention fatigue, and not from aesthetic preference and stimulation. This means that cities need to offer a range of qualities, for both stimulation and recovery. Based on that function, the results support the ART and CCT theories.

In this study we have included many types of greenery on facades. This way, we were able to identify many types of architectural attributes that are important for recovery from high stress levels and attention fatigue. It is crucial to conduct studies on the demands of citizens and users of urban spaces and building facades. These studies can assist building designers in implementing more suitable designs that meet the needs of users. By prioritizing this issue, we can improve the quality of urban living environments and positively impact people's perceptions of the city's image for their mental rejuvenation. Neglecting to conduct such studies can lead to a gap between users' wishes and designers' preferences for plans, resulting in poorly designed spaces that do not meet users' needs.

However, it is important to acknowledge the limitations of this study when interpreting the results. Firstly, the survey was exploratory, and the budget was limited, which may have affected the representativeness of the sample size of 204 respondents in relation to the demographics of the study area. People with different demographic attributes and ethnic backgrounds may have different opinions. The subjects in this study mainly consisted of young academics. Future studies should include a larger and more representative sample of subjects, especially regarding age, ethnic background and education. Secondly, the selection and arrangement of components and their levels in the design of images have influenced the results, due to the limitation in the number of components associated with the discrete selection method, which should be considered in future studies. The number of alternatives in the selection set was reduced to save time and money and generate the most reliable results. Thirdly, considering the limitations of time, money, and facilities, the facades studied in this research are of residential buildings, and photographic surrogates were used instead of real environments. In future studies, it is suggested that realistically simulated projects be investigated and that more diverse landscapes, such as green facades of offices and commercial buildings and different residential buildings, be used to obtain more acceptable results.

**Author Contributions:** Conceptualization, M.P. and P.H.; methodology, M.P. and P.G.; software, M.P.; validation, M.P., P.G. and H.N.; formal analysis, M.P. and H.N.; investigation, M.P., P.G. and H.N.; resources, M.P. and P.H.; data curation, P.H.; writing—original draft preparation, M.P., P.H. and H.N.; writing—review and editing, M.P., P.G. and H.N.; supervision, M.P.; project administration, M.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** Part of this study has been funded by the FORMAS Research Council; the project 'Sustainable outdoor living environments—systematic interdisciplinary studies of health effects and impact on social inequalities' (D-nr 2019-01916).

**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** This article was inspired by the first author's master's thesis in architecture, entitled "Design of the green facade of residential building in order to ART of citizens Golestan Province, Iran", and a project (Project No: 1582) completed at the Department of Engineering, Faculty of Architecture, Golestan University.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. White, M.P.; Elliott, L.R.; Grellier, J.; Economou, T.; Bell, S.; Bratman, G.N.; Cirach, M.; Gascon, M.; Lima, M.L.; Lõhmus, M.; et al. Associations between green/blue spaces and mental health across 18 countries. *Sci. Rep.* **2021**, *11*, 8903. [CrossRef] [PubMed]
2. Kley, S.; Dovbishchuk, T. How a lack of green in the residential environment lowers the life satisfaction of city dwellers and increases their willingness to relocate. *Sustainablity* **2021**, *13*, 3984. [CrossRef]
3. Buckland, M.; Pojani, D. Green space accessibility in Europe: A comparative study of five major cities. *Eur. Plan. Stud.* **2023**, *31*, 146–167. [CrossRef]
4. White, E.V.; Gatersleben, B. Greenery on residential buildings: Does it affect preferences and perceptions of beauty? *J. Environ. Psychol.* **2011**, *31*, 89–98. [CrossRef]
5. Manso, M.; Teotónio, I.; Silva, C.M.; Cruz, C.O. Green roof and green wall benefits and costs: A review of the quantitative quantitative evidence. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110111. [CrossRef]
6. Matos Silva, C.; Bernardo, F.; Manso, M.; Loupa Ramos, I. Green Spaces over a Roof or on the Ground, Does It Matter? The Perception of Ecosystem Services and Potential Restorative Effects. *Sustainability* **2023**, *15*, 5334. [CrossRef]
7. Bornioli, A.; Subiza-pérez, M. Restorative urban environments for healthy cities: A theoretical model for the study of restorative experiences in urban built settings. *Landsc. Res.* **2022**, *48*, 152–163. [CrossRef]
8. Li, X.; Zhang, X.; Jia, T. Humanization of nature: Testing the influences of urban park characteristics and psychological factors on collegers' perceived restoration. *Urban For. Urban Green.* **2023**, *79*, 127806. [CrossRef]
9. Labib, S.M.; Lindley, S.; Huck, J.J. Estimating multiple greenspace exposure types and their associations with neighbourhood premature mortality: A socioecological study. *Sci. Total Environ.* **2021**, *789*, 147919. [CrossRef]
10. Galindo, M.A.P.; Hidalgo, M.A.C. Aesthetic preferences and the attribution of meaning: Environmental categorization processes in the evaluation of urban scenes. *Int. J. Psychol.* **2005**, *40*, 19–26. [CrossRef]
11. Velarde, M.D.; Fry, G.; Tveit, M. Health effects of viewing landscapes–Landscape types in environmental psychology. *Urban For. Urban Green.* **2007**, *6*, 199–212. [CrossRef]
12. Kaplan, R.; Kaplan, S. *The Experience of Nature: A Psychological Perspective*; Cambridge University Press: Cambridge, UK, 1989.
13. Basu, A.; Duvall, J.; Kaplan, R. Attention Restoration Theory: Exploring the Role of Soft Fascination and Mental Bandwidth. *Environ. Behav.* **2019**, *51*, 1055–1081. [CrossRef]
14. Herzog, T.R.; Maguire, C.P.; Nebel, M.B. Assessing the restorative components of environments. *J. Environ. Psychol.* **2003**, *23*, 159–170. [CrossRef]
15. Grahn, P.; Ottosson, J.; Uvnäs-Moberg, K. The Oxytocinergic System as a Mediator of Anti-stress and Instorative Effects Induced by Nature: The Calm and Connection Theory. *Front. Psychol.* **2021**, *12*, 617814. [CrossRef] [PubMed]
16. Stoltz, J.; Grahn, P. Perceived sensory dimensions: Key aesthetic qualities for health-promoting urban green spaces. *J. Biomed. Res.* **2021**, *2*, 22–29.
17. Grahn, P.; Stigsdotter, U.K. The relation between perceived sensory dimensions of urban green space and stress restoration. *Landsc. Urban Plan.* **2010**, *94*, 264–275. [CrossRef]
18. Kaplan, R. Employees' reactions to nearby nature at their workplace: The wild and the tame. *Landsc. Urban Plan.* **2007**, *82*, 17–24. [CrossRef]
19. Memari, S.; Pazhouhanfar, M. Role of Kaplan's Preference Matrix in the Assessment of Building façade, Case of Gorgan, Iran. *Arman. Archit. Urban Dev.* **2017**, *10*, 13–25. Available online: https://www.researchgate.net/publication/329774419 (accessed on 5 August 2023).
20. Pazhouhanfar, M.; Davoodi, S.R.; Kamal, M. Effect of characteristics of Urban natural landscapes in increasing perceived restorative potential of urban environments. *Sci. Res. Essays.* **2013**, *8*, 885–889.
21. Mladenović, E.; Lakićević, M.; Pavlović, L.; Hiel, K.; Padejčev, J. Opportunities and benefits of green balconies and terraces in urban conditions. *Contemp. Agric.* **2017**, *66*, 38–45. [CrossRef]

22. Zhong, W.; Schröder, T.; Bekkering, J. Biophilic design in architecture and its contributions to health, well-being, and sustainability: A critical review. *Front. Archit. Res.* **2022**, *11*, 114–141. [CrossRef]
23. Carpenter, S. A Guide to Green Roofs, Walls and Facades in Melbourne and Victoria, Australia. State of Victoria through the Department of Environment and Primary Industries. Print. 2014. Available online: https://www.melbourne.vic.gov.au/SiteCollectionDocuments/growing-green-guide.pdf (accessed on 9 September 2023).
24. Elsadek, M.; Liu, B.; Lian, Z. Green façades: Their contribution to stress recovery and well-being in high-density cities. *Urban For. Urban Green.* **2019**, *46*, 126446. [CrossRef]
25. Aletta, F.; Xiao, J. Handbook of Research on Perception-Driven Approaches to Urban Assessment and Design. *Handb. Res. Percept. -Driven Approaches Urban Assess. Des.* **2018**, *i*, 1–641.
26. Lotfi, Y.A.; Refaat, M.; El Attar, M.; Abdel Salam, A. Vertical gardens as a restorative tool in urban spaces of New Cairo. *Ain Shams Eng. J.* **2020**, *11*, 839–848. [CrossRef]
27. Kozamernik, J.; Rakuša, M.; Nikšic, M. How green facades affect the perception of urban ambiences: Comparing Slovenia and the Netherlands. *Urbani Izziv.* **2020**, *31*, 88–100. [CrossRef]
28. Sadeghifar, M.; Pazhouhanfar, M.; Farrokhzad, M. An exploration of the relationships between urban building façade visual elements and people's preferences in the city of Gorgan, Iran. *Archit. Eng. Des. Manag.* **2019**, *15*, 445–458. [CrossRef]
29. Alishah, M.; Ebrahimi, A.; Ghaffari, F. The Role of Buildings Facades of on Urban Landscape (Case Study: Old Context of Sari). *Turk. Online J. Des. Art. Commun.* **2016**, *6*, 1347–1356. [CrossRef]
30. Masoud Lavasani, M. Experience of constituting residential facade in district 17 of Tehran. MANZAR. *Sci. J. Landsc.* **2014**, *6*, 50–55.
31. van den Berg, A.E.; Koole, S.L.; van der Wulp, N.Y. Environmental preference and restoration: (How) are they related? *J. Environ. Psychol.* **2003**, *23*, 135–146. [CrossRef]
32. Beute, F.; de Kort, Y.A.W. Thinking of nature: Associations with natural versus urban environments and their relation to preference. *Landsc. Res.* **2019**, *44*, 374–392. [CrossRef]
33. Nasar, J.L. New developments in aesthetics for urban design. In *Toward the Integration of Theory, Methods, Research, and Utilization*; Springer: Berlin/Heidelberg, Germany, 1997; pp. 149–193.
34. Nawrath, M.; Kowarik, I.; Fischer, L.K. The influence of green streets on cycling behavior in European cities. *Landsc. Urban Plan.* **2019**, *190*, 103598. [CrossRef]
35. Staats, H.; Swain, R. Cars, trees, and house prices: Evaluation of the residential environment as a function of numbers of cars and trees in the street. *Urban For. Urban Green.* **2020**, *47*, 126554. [CrossRef]
36. van Vliet, E.; Dane, G.; Weijs-Perrée, M.; van Leeuwen, E.; van Dinter, M.; van den Berg, P.; Borgers, A.; Chamilothori, K. The influence of urban park attributes on user preferences: Evaluation of virtual parks in an online stated-choice experiment. *Int. J. Environ. Res. Public Health* **2021**, *18*, 212. [CrossRef] [PubMed]
37. Zhang, Y.; Van den Berg, A.E.; Van Dijk, T.; Weitkamp, G. Quality over quantity: Contribution of urban green space to neighborhood satisfaction. *Int. J. Environ. Res. Public Health* **2017**, *14*, 535. [CrossRef]
38. De Jong, K.; Albin, M.; Skärbäck, E.; Grahn, P.; Björk, J. Perceived green qualities were associated with neighborhood satisfaction, physical activity, and general health: Results from a cross-sectional study in suburban and rural Scania, southern Sweden. *Health Place* **2012**, *18*, 1374–1380. [CrossRef]
39. Bertamini, M.; Rampone, G.; Makin, A.D.J.; Jessop, A. Symmetry preference in shapes, faces, flowers and landscapes. *PeerJ* **2019**, *2019*, e7078. [CrossRef]
40. Azemati, H.; Jam, F.; Ghorbani, M.; Dehmer, M.; Ebrahimpour, R.; Ghanbaran, A.; Emmert-Streib, F. The role of symmetry in the aesthetics of residential building façades using cognitive science methods. *Symmetry* **2020**, *12*, 1438. [CrossRef]
41. Leder, H.; Tinio, P.P.L.; Brieber, D.; Kröner, T.; Jacobsen, T.; Rosenberg, R. Symmetry Is Not a Universal Law of Beauty. *Empir. Stud. Arts.* **2019**, *37*, 104–114. [CrossRef]
42. Shr, Y.H.; Ready, R.; Orland, B.; Echols, S. How Do Visual Representations Influence Survey Responses? Evidence from a Choice Experiment on Landscape Attributes of Green Infrastructure. *Ecol. Econ.* **2019**, *156*, 375–386. [CrossRef]
43. Van Dongen, R.P.; Timmermans, H.J.P. Preference for different urban greenscape designs: A choice experiment using virtual environments. *Urban For. Urban Green.* **2019**, *44*, 126435. [CrossRef]
44. Chen, G. *Landscape Architecture: Planting Design Illustrated*; ArchiteG, Inc.: Irvine, CA, USA, 2011.
45. Ghomeshi, M.; Jusan, M.M. Investigating different aesthetic preferences between architects and non-architects in residential façade designs. *Indoor Built Environ.* **2013**, *22*, 952–964. [CrossRef]
46. Hossein Askari, A.; Dola, K.B.; Soltani, S. An evaluation of the elements and characteristics of historical building façades in the context of Malaysia. *Urban Des. Int.* **2014**, *19*, 113–124. [CrossRef]
47. Kennedy, R.; Buys, L. The impact of private and shared open space on liveability in subtropical apartment buildings. In *Global interchanges: Resurgence of the skyscraper city (Proceedings of the CTBUT 2015 International Conference)*; The Council on Tall Buildings and Urban Habitat (CTBUT): Chicago, IL, USA, 2015; pp. 318–323.
48. Kaplan, S.; Kaplan, R.; Wendt, J.S. Rated preference and complexity for natural and urban visual material. *Perception Psychophysics* **1972**, *12*, 354–356. [CrossRef]
49. Kaplan, S.; Kaplan, R. *Cognition and Environment: Functioning in an Uncertain World*; Ulrichs Books: Ann Arbor, MI, USA, 1989.

50. Fabrigar, L.R.; Wegener, D.T. *Exploratory Factor Analysis*; Oxford University Press: Oxford, UK, 2011.
51. Mangone, G.; Dopko, R.L.; Zelenski, J.M. Deciphering landscape preferences: Investigating the roles of familiarity and biome types. *Landsc. Urban Plan.* **2021**, *214*, 104189. [CrossRef]
52. Adevi, A.A.; Grahn, P. Preferences for landscapes: A matter of cultural determinants or innate reflexes that point to our evolutionary background? *Landsc. Res.* **2012**, *37*, 27–49. [CrossRef]
53. Gyllin, M.; Grahn, P. Semantic Assessments of Experienced Biodiversity from Photographs and On-Site Observations—A Comparison. *Environ. Nat. Resour. Res.* **2015**, *5*, 46. [CrossRef]
54. Gandy, R.; Meitner, M.J. The effects of an advanced traveler information system on scenic beauty ratings and the enjoyment of a recreational drive. *Landsc. Urban Plan.* **2007**, *82*, 85–93. [CrossRef]
55. Maulan, S. A Perceptual Study of Wetlands: Implications for Wetland Restoration in the Urban Area in Malaysia. Ph.D. Thesis, Virginia Tech, Blacksburg, VA, USA, 2006.
56. Kaplan, L.V. Introduction. *Int. J. Law. Psychiatry* **1980**, *3*, 211. [CrossRef]
57. Selangor, D.E.; Proffesor, A. Utilizing a photo-analysis software for content identifying method (CIM). *J. Landsc. Ecol.* **2015**, *8*, 32–55.
58. Hami, A. Indoor and Built Students' landscaping preferences for open spaces for their campus environment. *Indoor Built Environ.* **2021**, *30*, 87–98. [CrossRef]
59. Hami, A.; Fazle, F.; Bin, S. Urban Forestry & Urban Greening Public preferences toward shopping mall interior landscape design in Kuala. *Urban For. Urban Green.* **2018**, *30*, 1–7.
60. Deghati, M.; Atiah, N.; Maulan, S. Visual preference dimensions of historic urban areas: The determinants for urban heritage conservation. *Habitat. Int.* **2015**, *49*, 115–125. [CrossRef]
61. Stoltz, J.; Lundell, Y.; Skärbäck, E.; van den Bosch, M.A.; Grahn, P.; Nordström, E.M.; Dolling, A. Planning for restorative forests: Describing stress-reducing qualities of forest stands using available forest stand data. *Eur. J. For. Res.* **2016**, *135*, 803–813. [CrossRef]
62. Kamjoo, J.; Parviz, S.; Akhlaq, K.; Fitras, R.; Mohammad Hassan, D. Estimating the preferences of indigenous and non-indigenous citizens in dealing with Zayandehrood ecosystem services: A selection modeling approach (persian). *Q. J. Energy Econ. Stud.* **2019**, *10*, 1–24.
63. Campagnaro, T.; Vecchiato, D.; Arnberger, A.; Celegato, R.; Da Re, R.; Rizzetto, R.; Semenzato, P.; Sitzia, T.; Tempesta, T.; Cattaneo, D. General, stress relief and perceived safety preferences for green spaces in the historic city of Padua (Italy). *Urban For. Urban Green.* **2020**, *52*, 126695. [CrossRef]
64. Chang, K.G.; Chien, H. The influences of landscape features on visitation of hospital green spaces—A choice experiment approach. *Int. J. Environ. Res. Public Health* **2017**, *14*, 724. [CrossRef]
65. Sezavar, N.; Pazhouhanfar, M.; Van Dongen, R.P.; Grahn, P. The importance of designing the spatial distribution and density of vegetation in urban parks for increased experience of safety. *J. Clean. Prod.* **2023**, *403*, 136768. [CrossRef]
66. Shayestefar, M.; Pazhouhanfar, M.; Van Oel, C.; Grahn, P. Exploring the Influence of the Visual Attributes of Kaplan' s Preference Matrix in the Assessment of Urban Parks: A Discrete Choice Analysis. *Sustainability* **2022**, *14*, 7357. [CrossRef]
67. Hashemi, S.M.; Mahdieh, K. Role of physical attributes of preferred building facades on perceived visual complexity: A discrete choice experiment. *Environ. Dev. Sustain.* **2023**, 0123456789. [CrossRef]
68. Train, K.E. *Discrete Choice Methods with Simulation*; Cambridge University Press: Cambridge, UK, 2009.
69. Cochran IW, G.; Cox, G.M. *Experimental Designs*; Wiley: New York, NY, USA, 1957.
70. Stolle, D.P.; Robbennolt, J.K.; Patry, M.; Penrod, S.D. Fractional factorial designs for legal psychology. *Behav. Sci. Law.* **2002**, *20*, 5–17. [CrossRef]
71. Hensher, D.A.; Rose, J.M.; Rose, J.M.; Greene, W.H. *Applied Choice Analysis: A Primer*; Cambridge University Press: Cambridge, UK, 2005.
72. Arnberger, A.; Eder, R. Are urban visitors' general preferences for green-spaces similar to their preferences when seeking stress relief? *Urban For. Urban Green.* **2015**, *14*, 872–882. [CrossRef]
73. Lottrup, L.; Grahn, P.; Stigsdotter, U.K. Workplace greenery and perceived level of stress: Benefits of access to a green outdoor environment at the workplace. *Landsc. Urban Plan.* **2013**, *110*, 5–11. [CrossRef]
74. Kaplan, S. The restorative benefits of nature: Toward an integrative framework. *J. Environ. Psychol.* **1995**, *15*, 169–182. [CrossRef]
75. Grahn, P.; Stoltz, J.; Bengtsson, A. The Alnarp Method: An interdisciplinary-based design of holistic healing gardens derived from research and development in Alnarp Rehabilitation Garden. In *Routledge Handbook of Urban Landscape Research*; Routledge: London, UK, 2022; pp. 299–317.
76. Fu, H.; Xue, P. Cognitive restoration in following exposure to green infrastructure: An eye-tracking study. *J. Green. Build.* **2023**, *18*, 65–88. [CrossRef]
77. Blamey, R.K.; Bennett, J.W.; Louviere, J.J.; Morrison, M.D.; Rolfe, J. A test of policy labels in environmental choice modelling studies. *Ecol. Econ.* **2000**, *32*, 269–286. [CrossRef]

78. Bengtsson, A.; Grahn, P. Outdoor environments in healthcare settings: A quality evaluation tool for use in designing healthcare gardens. *Urban For. Urban Green.* **2014**, *13*, 878–891. [CrossRef]
79. Memari, S.; Pazhouhanfar, M.; Grahn, P. Perceived sensory dimensions of green areas: An experimental study on stress recovery. *Sustainability* **2021**, *13*, 5419. [CrossRef]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

*Article*

# Thermal–Acoustic Interaction Impacts on Crowd Behaviors in an Urban Park

**Ye Chen [1,2], Ziyi Chen [1,2], Shumeng Lin [1,2], Xiaoqian Lin [1,2], Shuting Li [3], Taoyu Li [4] and Jianwen Dong [1,2,*]**

[1] College of Landscape Architecture and Art, Fujian Agriculture and Forestry University, 15 Shangxiadian Rd., Fuzhou 350000, China; 2191775001@fafu.edu.cn (Y.C.); 3211726008@fafu.edu.cn (Z.C.); 1221775066@fafu.edu.cn (S.L.); 1221775002@fafu.edu.cn (X.L.)
[2] Engineering Research Center for Forest Park of National Forestry and Grassland Administration, 63 Xiyuangong Rd., Fuzhou 350002, China
[3] College of Economics and Management, Fujian Agriculture and Forestry University, 15 Shangxiadian Rd., Fuzhou 350000, China; 000q822019@fafu.edu.cn
[4] Xiamen Tobacco Industry Co., Ltd., 1 Xinyang Rd., Xiamen 361000, China; lty23208@fjtic.cn
* Correspondence: fjdjw@fafu.edn.cn

**Abstract:** As urbanization accelerates, parks, as vital urban public open spaces, and their acoustic and thermal ambience directly impact visitors' comfort and the sustainability of parks. Selecting Xihu Park in Fuzhou, China located in the subtropical region as a typical example, this study utilizes covert observational experiments with different typical sounds (grass cutting, music, and no sound source) across temperature levels to examine the influence of thermal–acoustic interactions on crowd behaviors in the park. The findings are as follows: (1) melodious music can attract more tourists, while strong stimulating grass cutting noises under high temperatures reduce crowd flow. Excluding unpleasant audio sources, park soundscapes across temperatures have a relatively limited influence on attractiveness to people flow. (2) High temperatures diminish tourists' interest in landscape experiences and persons staying, especially when the soundscape quality is poorer. Under non-high temperatures, audio environments have a minor impact on the staying time. (3) The soundscape quality plays a role by affecting people's path choices of approaching or avoiding sound sources, where grass cutting noise has the most negative influence. Music, grass cutting sounds, and natural sounds demonstrate conspicuous differences in their effects under varied temperatures. (4) Comfortable acoustic environments can draw larger crowds and decrease the walking pace. High temperatures make crowds take slower steps. Different sound types have significant influences on crowd movement velocity under three typical temperature levels. This study comprehensively investigates the mechanisms of typical thermal–acoustic environments' impacts on park crowd behaviors, providing important references for optimizing the acoustic and thermal environments of urban parks, while also enriching related research on landscape design and environmental psychology. Future studies can conduct in-depth explorations by creating more abundant thermal–acoustic combinations and probe differences across diverse populations.

**Keywords:** urban park; crowd behavior; temperature; acoustic; Fuzhou city; soundscape

**Citation:** Chen, Y.; Chen, Z.; Lin, S.; Lin, X.; Li, S.; Li, T.; Dong, J. Thermal–Acoustic Interaction Impacts on Crowd Behaviors in an Urban Park. *Forests* **2023**, *14*, 1758. https://doi.org/10.3390/f14091758

Academic Editors: Guangyu Wang, Chi Yung Jim, Jiang Liu, Xin-Chen Hong, Jinda Qi, Baojie He and Shi Cheng

Received: 4 August 2023
Revised: 23 August 2023
Accepted: 29 August 2023
Published: 30 August 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The breakneck urbanization of the 21st century has spawned manifold environmental predicaments, including water scarcity [1,2], waste accumulation [3], soil contamination [4], overpopulation [5], noise pollution [6], and the specter of climate change [7]. Of particular concern is the pernicious impact of outdoor noise on human health [8–11]. Scientific research corroborates that chronic exposure to cacophony can precipitate hearing impairment, disrupted sleep, and heightened risks of cardiovascular and mental illness. Moreover, the direct repercussions of climate change and the emergence of the urban heat island effect

have bred thermal discomfort in urban areas [12–14]. Nevertheless, urban parks have materialized as an indispensable component of the comprehensive urban ecosystem network, proffering a myriad of benefits for city dwellers [15]. The abundance of sprawling greenery within these parks works to bolster physical and mental well-being, effectively mitigating exposure to air and noise pollution, as well as extreme temperatures. Furthermore, they furnish a sanctuary for psychological relaxation and stress relief [16,17].

Furthermore, urban parks are the cornerstone for the existence, function, and growth of cities [18]. Diverse sensory cues continuously shape people's lifestyles. Thus, the sensory design of municipal green spaces is garnering mounting attention. However, the prevailing issue is the disproportionate prioritization of visual appeal over other sensory modalities. This results in the satisfaction of aesthetic preferences at the sacrifice of visitors' holistic sensory and psychological well-being [19–21].

Moreover perceiving various attributes of the external world makes important contributions to humans' complex cognitive processes, as perception is the cornerstone of many psychological processes [22]. All understanding of the world stems from perception. Moreover, multi-sensory integration can garner richer, more comprehensive information. Existing multi-sensory research has focused primarily on audiovisual [23] and visual–olfactory [24] interactions, while research on thermal–acoustic environment interactions has been limited. For instance, Pellerin (2010) believes initial thermal–acoustic conditions influence subjective sound–heat perception. In noisy environments, noise is the decisive factor. Only when ambient temperature diverges markedly from thermal comfort does temperature become decisive. Additionally, under thermal conditions, noise affects thermal comfort—higher noises increase thermal discomfort at elevated ambient temperatures [25,26]. Concurrently, when environmental temperature differs substantially from subjective thermal perception, auditory perception is weakened. These experiments confirm that different thermal–acoustic combinations can impact psychological parameters and subjective evaluations.

Changes in the sensory environment impact people's psychology. As a result, psychological perception shifts will inevitably lead to corresponding behavioral changes. In sensory environment assessments, behavior plays an important role, as surrounding crowd activities and actions are a critical part of the environment [27]. However, urban park designs are far from ideal due to insufficient research on crowd behavior within them. Hence, it is imperative to study crowd behavior in urban parks.

Based on different research objects, behavior is divided into individual and crowd behavior. Individual behavior typically refers to personal attitudes or performances under specific circumstances, which are largely random under environmental influences [28]. Crowd behavior denotes the activities of groups of people in an environment, following certain regularities [29,30]. Hence, scholars often pay more attention to crowd, rather than individual, behavior when studying urban parks [31]. According to characteristics, crowd behavior can be categorized into movement and action. Movement behaviors include passing through, circling around, and staying still, while actions encompass sitting, standing, sightseeing, and strolling [32]. Movement behaviors can better reflect overall crowd trends, while the scope and extent of the influence on action behaviors are relatively smaller. Research shows that sensory environments impact human behavior. For acoustic influences, music sound is a common auditory stimulus. The presence of music guides crowds to exhibit orientation behaviors towards the sound source, slowing down the pace. Additionally, sitting crowd density decreases with an increasing distance from the source [28,33]. Moreover, music can increase the crowd dwelling time in locations, like pavilions, garden paths, and park plazas, with the music genre also potentially affecting results [34,35]. Thermal environments likewise influence action behaviors, with people exhibiting different evaluations and actions under varying park temperatures [36]. Currently, related research on the thermal–acoustic interaction's impact on crowd behavior to improve urban park utilization remains limited. Overall, studies exploring the relationship

between sound and temperature and their influence on crowd behavior to enhance urban park use are scarce.

This study conducted covert behavioral observation experiments in a typical urban park, using low-, medium-, and high-heat temperatures as different temperature levels, while replicating typical urban park music sound sources and lawn mower sounds (as well as no sound conditions). The aim was to examine the regularities of crowd movement behaviors under the interaction of sound and temperature, thereby improving the utilization of urban parks. The research questions addressed in this study are as follows: (1) the impact of thermal–acoustic interactions on the number of people; (2) the impact of thermal–acoustic interactions on the number of persons staying; (3) the impact of thermal–acoustic interactions on path offset; (4) the impact of thermal–acoustic interactions on crowd speed.

## 2. Materials and Methods

### *2.1. Study Site Overview*

This research was conducted in Fuzhou, a typical city in the humid subtropical region of China. Fuzhou has a pleasant and humid climate with evergreen seasons, abundant sunshine, and rainfall, as well as a short winter and long summer. The frost-free period reaches up to 326 days annually. The average annual sunshine hours are between 1700 and 1980, and the average annual rainfall is between 900 and 2100 mm. The average annual temperature is 20–25 °C, with the coldest month being December, with an average temperature of 6–10 °C, and the hottest month being July and August, with an average temperature of 33–37 °C. The extreme temperatures range from 2.5 to 42.3 °C annually. The average relative humidity is about 77%, and the city often experiences the urban heat island effect due to its basin topography, where the temperature can reach over 36 °C at noon in the summer. The dominant wind direction is northeast, with south wind prevailing in summer [37]. The research site was selected based on whether it had the common sound sources and thermal environments found in urban parks. To investigate the effect of the thermal acoustic environment on subjective evaluations of urban parks, taking into account factors, such as the park area and its accessibility, the Xihu Park located in the city center was finally chosen.

Xihu Park is located in the northwest part of Gulou District, Fuzhou City, and is situated at the city's center, adjacent to residential, commercial, and office areas in the city center. It is only a 700 m away from the main transportation artery Yangqiao East Road and can be reached by a 10 min walk. With a history of more than 1700 years, it is the most well-preserved classical garden in Fuzhou, and it is renowned as the "Pearl of Fujian Gardens", ranking among the top 36 West Lakes in the country. Currently, it covers an area of 42.51 hectares, with a land area of 12.21 hectares and a water area of 30.3 hectares. The vegetation composition in Xihu Park is complex, dominated by forests, grasslands, shrub beds and flower gardens. The forest area is relatively large, consisting primarily of deciduous and mixed coniferous forests. The deciduous broad-leaved forest in the Huxin Mountain is the most typical, characterized by dominant tree species, such as nanmu, camphor, banyan, and paulownia, forming a natural, primitive and spectacular ecosystem. The grasslands consist of common lawn grass and some wildflowers, while the shrubs are composed of flower bushes and some climbing plants. The rich and diverse vegetation composition of Xihu Park is functionally complete, providing an ideal place for urban ecological construction, as well as for citizens to relax, exercise, and enjoy their leisure time [38].

There were a total of 2 sample sites in Xihu Park. The panoramic view of these sites can be seen in the accompanying Figure 1. On a representative summer day (a weekday in September), crowd behavior observation and thermal acoustic monitoring was conducted.

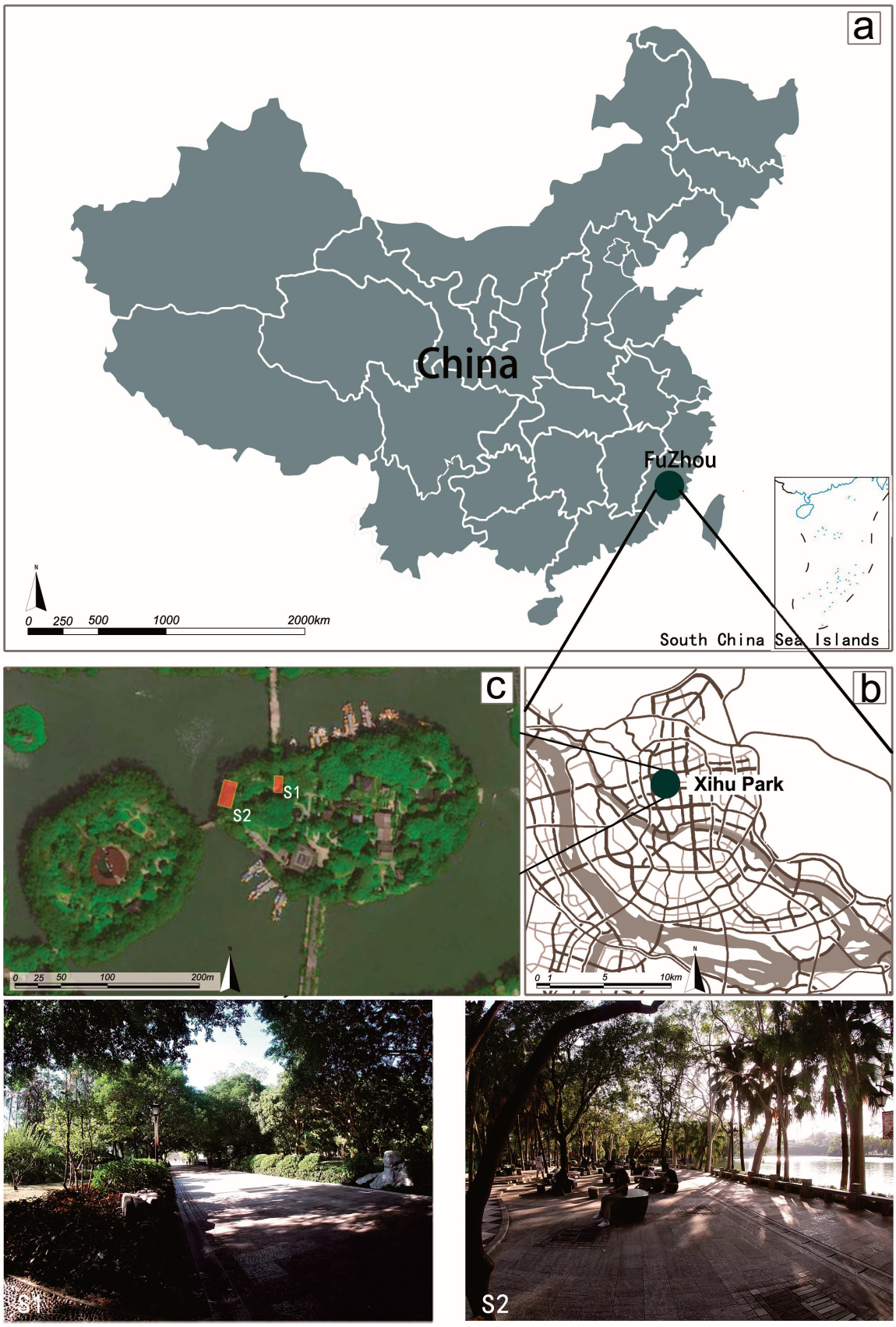



**Figure 1.** (**a**) Location of Fuzhou city in the China map; (**b**) Xihu Park in Fuzhou city; (**c**) S1 and S2 sample sites within Xihu Park.

### 2.2. Procedures

For objective acoustic indicators, this study has selected LAeq (A-weighted equivalent continuous sound level) as the primary monitoring metric owing to the discontinuity of park soundscapes [39]. For thermal environment metrics, the Universal Thermal Climate Index (UTCI) was chosen given the instability of outdoor thermal conditions [40]. UTCI denotes the equivalent temperature of a reference environment eliciting identical physiological responses as a standard individual in the actual environment. This index synthesizes subjective factors and objective environmental parameters, accounting for human thermal adaptability [32,41]. The UTCI value is derived from thermal environmental parameters gathered via the questionnaire. Once data on the radiation temperature, air temperature, relative humidity, wind speed, and mean radiant temperature are prepared, the UTCI can be calculated using either the BioKlima2.6 software or the Fortran program from the official website (http://www.utci.org accessed on 3 August 2023).The deviation of the UTCI from air temperature is determined by the actual air temperature (Ta), mean radiant temperature (Tmrt), wind speed (Va), and relative humidity (Rh). This can be expressed as follows [42]:

$$UTCI = Ta + Offset(Ta, Tmrt, Va, Rh) = f(Ta, Tmrt, Va, Rh) \quad (1)$$

where Ta denotes the temperature of a 2 m air column, Va denotes the wind speed at 10 ms, Pa denotes the relative humidity, and Tmrt denotes the average radiative temperature.

### 2.3. Selection of the Thermal–Acoustic Environment

In terms of urban parks, there is a rich variety of sounds, including natural sounds from the plant kingdom, such as birds singing, frogs croaking, insects chirping, and the rustling of leaves in the wind, among others. In addition, due to the extensive activities of people in the park, artificial noise is almost everywhere. Furthermore, maintenance work also generates noise, such as construction sounds, traffic noise, and the sound of machinery operating, among others. Therefore, it is rare for urban parks to have a single sound environment or to be completely silent. In comparison, controlling the thermal environment is relatively easier. However, in practical situations, it is difficult to find natural conditions that can simultaneously maintain sound consistency but vary in thermal conditions or maintain thermal consistency but vary in sound. Therefore, a field site with a controllable thermal environment was selected as the research area, and the combination of sound and thermal factors was controlled by playing sounds.

#### 2.3.1. Thermal Environment

Given the differences in lifestyles and urban environments among tourists, there are certain limitations to the soundscape experiment. This study primarily focuses on the conversation between individuals and natural soundscapes in a suitable warm environment, under normal temperature conditions for outdoor activities. For instance, outdoor activities are best suited during summer mornings and evenings. However, during midday, people may react to the intense sunlight, which could shift the focus of the sound environment observation experiment and consequently affect the accuracy of the data. When selecting the experimental site, the following factors should be considered: firstly, the thermal environment of the site should be relatively stable. Secondly, the sound pressure level and type of sound source in the sound environment should remain relatively stable, without any interference from sudden ambient sound sources. The selected observation site in the high-temperature area is located on the park road of Xihu Park in Fuzhou City. This road has minimal obstructions, and higher temperatures can be clearly felt when walking in the high-temperature area. The observation sites in the low- and medium-temperature areas are situated on the recreational plaza of Xihu Park in Fuzhou City. In the low- and medium-temperature environments, visitors have more options for activities, and the plaza provides enough seating to meet their needs.

The chosen observation site in the high-temperature region is located on the Garden Road in Xihu Park, Fuzhou. There are not many obstructions on this road, resulting in higher temperatures. While walking in the high-temperature region, one can clearly feel the heat wave hitting their face. The observation sites in the low-temperature and medium-temperature regions are situated on the leisure plaza in Xihu Park, Fuzhou. In the low-temperature and medium-temperature environments, visitors have a greater variety of activities to choose from, and the plaza provides ample seating to meet their needs. The UTCI difference among the low-temperature, medium-temperature, and high-temperature regions should be at least equal to or greater than 1.

#### 2.3.2. Acoustical Environment

This study considers using artificial voices as sound source variables through speakers, with both positive and negative impacts on humans. Ultimately, the researchers selected the typical sound sources of a lawn mower and music in a city park.

The lawn mower is a necessary tool for maintaining the normal quality of the park's lawn by trimming overgrown grass, making it a characteristic sound source in the park. Prior to the formal experiment, a pre-experiment was conducted to select the grass cutting sound [43]. Various grass cutting sounds from different city park environments were first chosen, followed by randomly selecting 30 participants to evaluate the annoyance level of these grass cutting sounds on a seven-point scale (not annoying 1-2-3-4-5-6-7 very annoying). The grass cutting sound with the highest score exceeding 6 was ultimately chosen as the sound source for this experiment.

Urban parks should provide a relaxing and comfortable atmosphere for people; therefore, when selecting the genre of music, consideration should be given to using light music. Light music refers to instrumental pieces within popular music, characterized by simple structure and beautiful melodies, creating a leisurely ambiance. The tempo of the music is also crucial in the selection process. According to research, a slow tempo is defined as 40–70 bpm, and a moderate tempo falls between 85 and 110 bpm, while anything above 120 bpm is considered fast-paced [44]. Furthermore, studies indicate that music below 80 bpm is associated with negative emotions and can lower the heart rate, whereas music above 120 bpm is linked to positive emotions but can increase the heart rate and breathing speed [45]. Therefore, choosing music with a moderate tempo is more suitable. Following careful research, the Urban Park finally decided to use "Snowdreams" by Bandari, a track that has gained popularity based on online charts, with a tempo of 85 bpm.

Therefore, in this study, sound variables were categorized into three conditions: the natural condition with no playing sounds, the condition of playing lawnmower sounds, and the condition of playing music sounds. When selecting the placement of speakers, several considerations were taken into account: firstly, ensuring that the sound is audible from any position within the area; secondly, maintaining a distance of at least 1.5 m between the front of the speaker and any reflective surfaces [46]; finally, in order to avoid any visual impact, the operators concealed the speakers within the research area [28].

### *2.4. Objective Measurement of the Sensory Environment*

The devices used in this study are delineated in Table 1. Before the experiments, the research area was divided into grids to enable subsequent measurements and analyses. The grid dimensions for the low-, medium-, and high-temperature test zones were uniformly established at 3 m × 3 m. To guarantee audibility of the speaker playback, the experimenter calibrated the sound pressure level above the background observed without playback and quantified the levels before and after playback to evaluate the acoustic settings. During the experiment, crowd density, as a dynamic factor, was consistently under 0.05 persons per square meter, allowing its impact on sound pressure and visual perception to be discounted [23,47].

**Table 1.** Measuring instruments and uses.

| Instrument | Example | Model | Use |
| --- | --- | --- | --- |
| Sound level meter | | BSWA801 | Measure the sound pressure level |
| Eight-channel high-fidelity recorder | | SQuadriga II<br>BHS I | Recording different kinds of sounds |
| Camera | | GoPro 7 | Recording crowd behavior |
| Handheld Mini Weather Station | | Kestrel5500 | Record air temperature, relative humidity, wind speed and direction |

### *2.5. Behavioural Observation*

To preclude the environmental influence, measurements were conducted on weekdays in September. Average temperatures that month ranged from 23 to 30 °C, with a relatively stable humidity and wind velocity and direction. Considering the importance of a sufficient sample size, testing times were chosen between 3 PM and 6 PM daily. To mitigate the observational impact on results, individuals were filmed with concealed cameras where typical acoustic factors were present. Participants were unaware of being observed. Each video lasted 20 min, and to ensure random behavior, three measurement sets were taken during each interval [29]. Both sound and silent conditions cycled throughout the experiment [48]. On testing days, no abrupt noises or temperature fluctuations interfered within the research area.

### *2.6. Analysis Method*

The experimental results comprise no missing values, and outliers were eliminated or replaced to ensure data accuracy and reliability. Post data collection and organization, objective parameters underwent standardization for calculating the mean and standard deviation of each variable.

In the production and experiments, outcomes relate to certain factors or result from multiple influences. Spearman correlation analysis is a non-parametric statistical method used primarily to evaluate the correlation between two ordinal or ranked variables [49]. Meanwhile, analysis of variance (ANOVA) is a technique inferring if one or more varied factors significantly impact the results. The observed data were analyzed using SPSS 27.0 software (developed by IBM, Armonk, NY, USA) in this study. To assess relationships between different sounds, temperature levels, and crowd behavior, Spearman analysis computed correlations between indicators. ANOVA examined differences in the thermal acoustic elements' impacts on crowd behavior, with Mauchly's sphericity test applied. When sphericity assumptions were violated ($p < 0.05$), corrections were performed—Greenhouse-Geisser for Epsilon < 0.75, Huynh-Feldt otherwise [50]. Experimental data underwent validation prior to analysis.

## 3. Results

### *3.1. Basic Environmental Conditions*

After measurements and calculations, the thermal environments in this study are shown in Figure 2a for the low-heat area, Figure 2b for the moderate-heat area, and Figure 2c for the high-heat area. The observation sites in the low- and moderate-heat areas were measured on-site using instruments, with UTCI values ranging from 28 °C to 30 °C in the low area and 30 °C to 31 °C in the moderate area. The high-heat area was measured on-site using instruments as well, with UTCI values consistently above 32 °C, sufficiently exhibiting the high temperature requirement of the high-heat area.

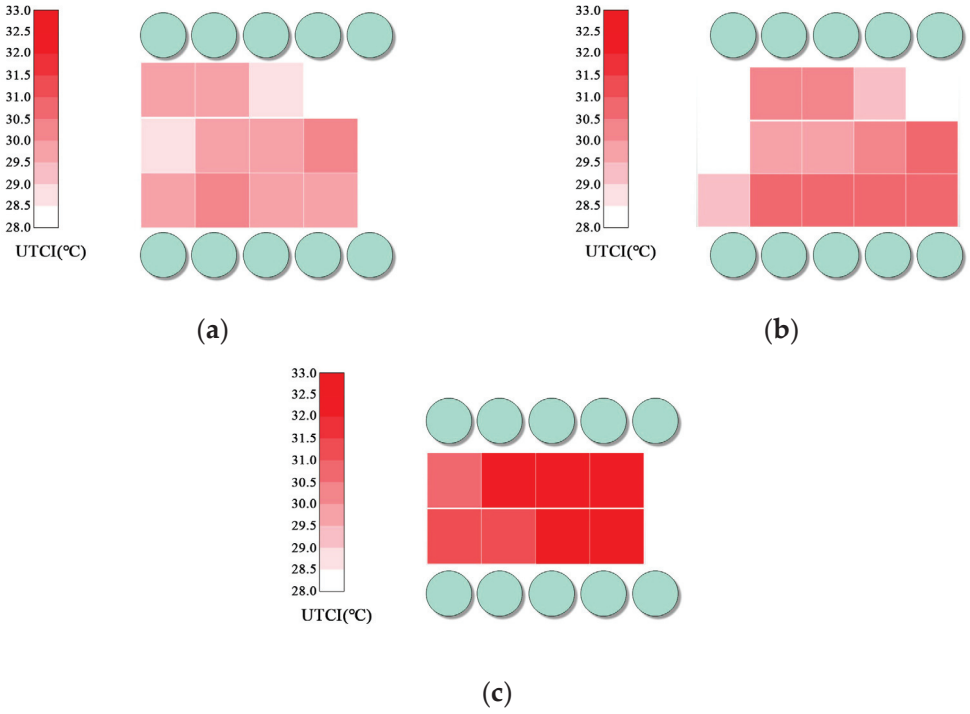



**Figure 2.** Thermal environment situation. (**a**) Low-heat area; (**b**) moderate-heat area; (**c**) high-heat area.

Figure 3a–c display the positions and sound pressure level variations for low- and medium-heat area sound sources. Meanwhile, Figure 3d–f exhibit the positions and variations for high-heat area sources (S denotes the source position). Table 2 provides sample statistics for the observed crowd behavior. During analysis, 50% of samples underwent random retesting, yielding consistent results with the total samples. This indicates sufficiently comprehensive samples and reliable outcomes.

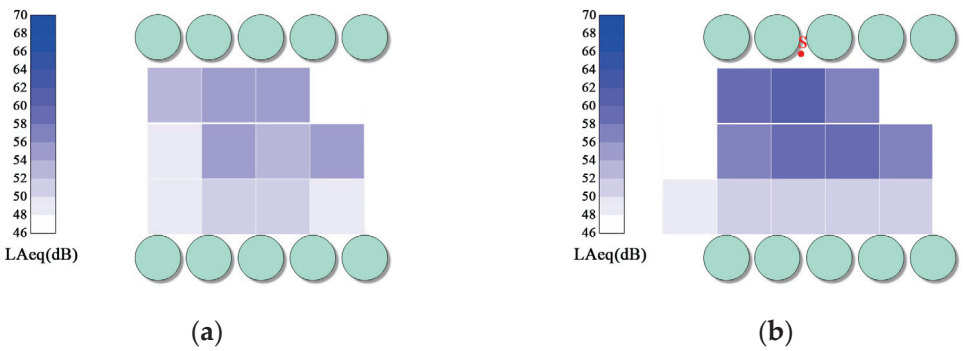



**Figure 3.** *Cont.*

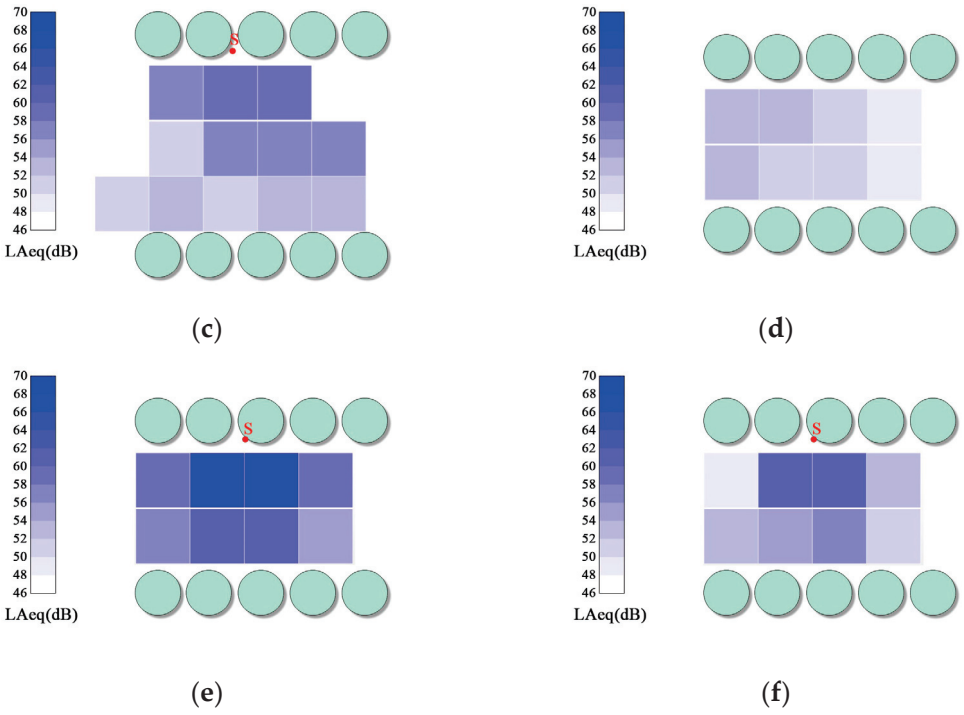



**Figure 3.** Acoustical environment situation: (**a**) without sound played in a low-heat and moderate-heat area; (**b**) with grass cutting sounds in low-heat and moderate-heat areas; (**c**) with music in low-heat and moderate-heat areas; (**d**) without sound played in high-heat area; (**e**) with grass-cutting sounds in high-heat area; (**f**) with music in high-heat area.

**Table 2.** The research samples of behavior observations.

| Temperature Level | Sound Type | Number of People | Number of Persons Staying | Path Offset | Crowd Speed |
|---|---|---|---|---|---|
| Low heat | Grass cutting | 97 | 4 | 0.128 | 1.348 |
| | The natural condition | 130 | 6 | 0 | 1.301 |
| | Music | 153 | 8 | −0.015 | 1.243 |
| Moderate heat | Grass cutting | 86 | 0 | 0.179 | 1.57 |
| | The natural condition | 143 | 5 | 0 | 1.39 |
| | Music | 102 | 10 | −0.196 | 1.378 |
| High heat | Grass cutting | 79 | 0 | 0.349 | 1.105 |
| | The natural condition | 97 | 0 | 0.02 | 1.031 |
| | Music | 102 | 0 | −0.118 | 1.077 |

### *3.2. Effects of the Thermal–Acoustic Interaction on the Number of People*

#### 3.2.1. The Number of People under the Thermal–Acoustic Interaction

Figure 4 shows the number of people under thermal–acoustic interactions. It can be observed that the number of people under the grass-cutting sound condition was consistently lower than that under the no sound and music conditions, decreasing slightly as the temperature rises. More specifically, under the grass-cutting sound condition, there were 97 people at low heat, 86 at moderate heat, and 79 at high heat. Overall, the grass-cutting sound attracted significantly fewer individuals than the other two sounds across different temperature conditions. In particular, the no-sound condition persistently involved the largest number of people, peaking under the moderate-heat condition. Namely, under the natural-sound condition there were 130 people at low heat, 143 at moderate heat, and 97 at high heat. In contrast, it can be observed that the number of people under the

music sound condition fluctuated under different temperature conditions. Specifically, the number of people was highest under the music sound condition at low heat, reaching 153; under the music sound condition at moderate heat, the number was 102, whereas at high heat, the number under the music sound condition was very close to the number under the no sound condition, both at 102 people.

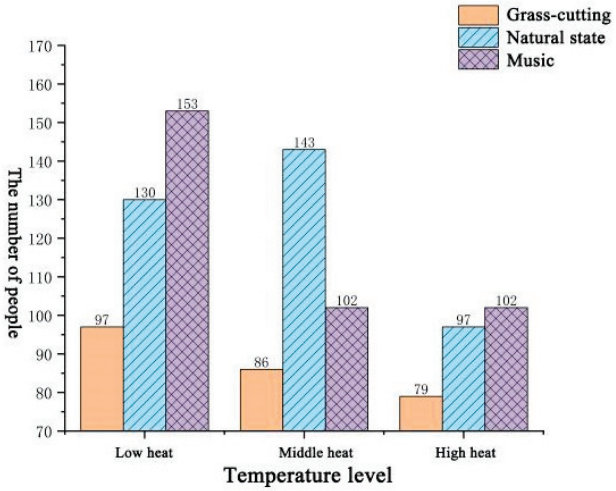



**Figure 4.** The number of people under the thermal–acoustic interaction.

3.2.2. Analysis of the Number of People under the Thermal–Acoustic Interaction

The analysis showed a correlation coefficient of 0.718 ($p = 0.03 < 0.05$) between sound types and the number of people (Table 3), indicating that good acoustics attract more people in urban parks. The coefficient between temperature and the number of people under grass cutting was −1 ($p = 0.00 < 0.01$) (Table 4), implying that high temperatures reduce crowds with stimulating sounds, like grass cutting. The temperature–crowd correlation was insignificant ($p = 0.166 > 0.1$), demonstrating that park acoustics do not markedly impact crowd attraction across temperatures without adverse noises. Prior studies show that people gravitate toward pleasing soundscapes. This further elucidates that good acoustics universally attract humans, whether the stimulus is single or multi-sensory.

**Table 3.** Correlation between the thermal–acoustic environment and the number of people.

| | | Sound Type | Temperature Level |
|---|---|---|---|
| Number of people | Correlation coefficient | 0.718 * | −0.505 |
| | Sig. (two-tailed) | 0.030 | 0.166 |

Note: * denotes $p$ (two-tailed) < 0.05. Sig. means significance.

**Table 4.** Correlation between the number of people and temperature under different sound types.

| | | Number of People under Grass-Cutting Condition | Number of People under Natural Condition | Number of People under Music Condition |
|---|---|---|---|---|
| Temperature level | Correlation coefficient | −1.000 ** | −0.500 | −0.866 |
| | Sig. (two-tailed) | 0.000 | 0.667 | 0.333 |

Note: ** denotes $p$ (two-tailed) < 0.01. Sig. means significance.

*3.3. Effects of the Thermal–Acoustic Interaction on the Number of Persons Staying*

3.3.1. The Number of Persons Staying under the Thermal–Acoustic Interaction

Figure 5 shows the number of persons staying under thermal–acoustic interactions. Under the grass-cutting sound condition, the number of persons staying was generally fewer than that under the no sound and music conditions and significantly decreased as

the temperature rose. Specifically, under the grass-cutting sound condition, there were 4 instances of persons staying under low heat, while under moderate- and high-heat, there were 0 instances. Overall, the number of persons staying under the grass-cutting sound was markedly lower than that under the other two sounds across different temperatures. Under the no-added-sound condition, the number of persons staying was highest under low heat. Namely, under natural conditions there were six instances of persons staying under low heat, five instances under moderate heat, and no one staying under high heat. The number of persons staying under the music-sound condition varied under different temperatures, with 8 instances under low heat, 10 instances under moderate heat, and also 0 instances under high heat.

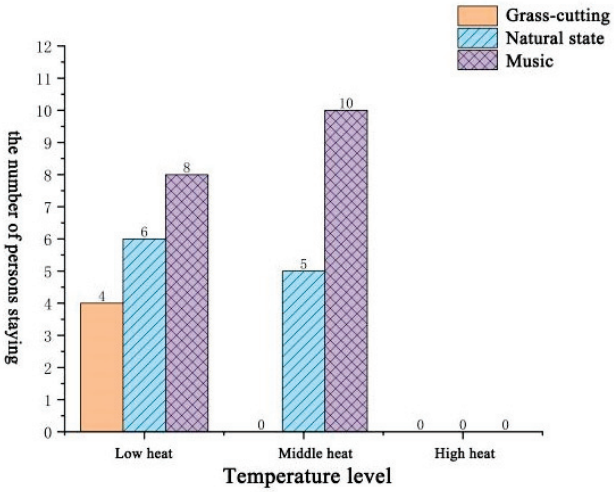



**Figure 5.** The number of persons staying under the thermal–acoustic interaction.

Additionally, under low-heat conditions, there were four instances of persons staying under the grass-cutting sound, six instances under the natural condition, and eight instances under the music sound. Therefore, under low temperature, the music sound attracted more people compared to the other two conditions. Under moderate heat, there were 0 instances under the grass-cutting sound, 5 instances under the natural condition, and 10 instances under the music sound. Hence, under medium temperature, the music sound had the best attraction effect, followed by the natural environment, while the grass-cutting sound had no attraction in this case. Under high heat, the number of persons staying was 0 under all three sound conditions. In summary, under high temperatures, no sound could effectively attract people to stay in the area regardless of audio interference.

3.3.2. Analysis of the Number of Persons Staying under the Thermal–Acoustic Interaction

According to Table 5, the correlation coefficient between temperature levels and the number of people staying was $-0.688$ ($p = 0.000 < 0.05$), meaning that in the urban park environment, the higher the temperature, the lower the tourists' willingness to stay and appreciate the scenery. In addition, Table 6 shows that the correlation coefficient between temperature levels and the number of persons staying under natural conditions was $-1$ ($p = 0.000 < 0.01$), implying that under high-temperature conditions, if there is no good sound environment stimulation, the number of persons staying will decrease. However, the correlation between sound types and the number of persons staying was not significant ($p = 0.149 > 0.1$), indicating that regardless of the sound type, as long as the temperature is not too high, the sound environment of urban parks does not have a significant impact on the attractiveness of the number of persons staying. Previous studies have shown that people tend to go to comfortable thermal environments, and this study further demonstrates that whether the stimulation is from a single-sense or multi-sensory interaction, a good thermal environment has universal appeal to human behavior.

**Table 5.** Correlation between the thermal–acoustic environment and the number of persons staying.

| | | Sound Type | Temperature Level |
|---|---|---|---|
| Number of persons staying | Correlation coefficient | 0.523 | −0.688 * |
| | Sig. (two-tailed) | 0.149 | 0.040 |

Note: * denotes $p$ (two-tailed) < 0.05. Sig. means significance.

**Table 6.** Correlation between the number of persons staying and temperature under different sound types.

| | | Number of Persons Staying under Grass-Cutting Condition | Number of Persons Staying under Natural Condition | Number of Persons Staying under Music Condition |
|---|---|---|---|---|
| Temperature level | Correlation coefficient | −0.866 | −1.000 ** | −0.500 |
| | Sig. (two-tailed) | 0.333 | 0.000 | 0.667 |

Note: ** denotes $p$ (two-tailed) < 0.01. Sig. means significance.

### *3.4. Effects of the Thermal–Acoustic Interaction on the Path Offset*

#### 3.4.1. The Path Offset under the Thermal–Acoustic Interaction

Figure 6 shows the path offset under the interaction of temperature and sound. When the grass-cutting sound was present, the mean path offsets were all positive values, and as the temperature rose, it resulted in a gradual upward trend in the path offset. Under moderate heat, it increased by 0.051 compared to under low heat and by 0.170 under high heat compared to under moderate heat. When no specific sound source was played, the path offsets under different temperature levels were all very small, basically maintained around 0. The only exception was when the temperature rose to 32 °C, the path offset became 0.02, but it was still a negligible increase. When light music was present, the mean path offsets were all negative values. Under low-heat conditions, the path offset was −0.015; under moderate heat, the path offset was −0.196, whereas under high heat, the path offset was −0.118.

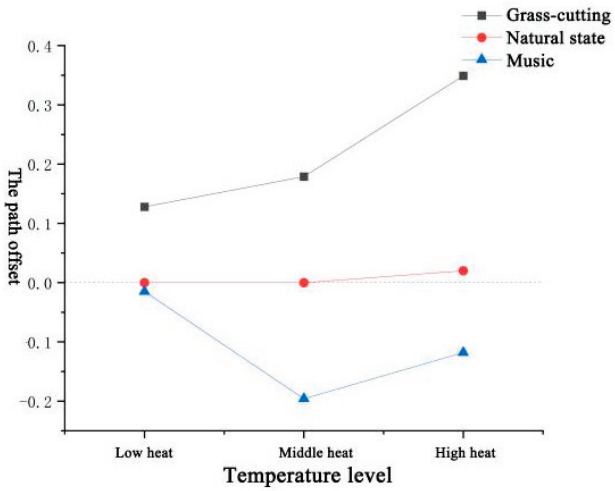



**Figure 6.** Path offset under the thermal–acoustic interaction.

In comparison, under low heat, the path offset under the grass-cutting sound was the largest, followed by that under music sound, while the path offset under natural conditions was the smallest at zero. In comparison, under moderate heat, the path offset under natural conditions remained 0, while the impacts of grass cutting and music sounds were more prominent in comparison. Under high heat, the path offset under the grass-cutting sound was the maximum at 0.349, higher than that under natural and music conditions.

3.4.2. Analysis of the Path Offset under the Thermal–Acoustic Interaction

The analysis results show that the correlation coefficient between sound types and path offset was −0.336 ($p = 0.000 < 0.01$), as shown in Table 7. This means that in the urban park environment, good soundscapes can attract tourists to approach the sound source, while undesirable sounds make visitors feel uneasy and stay away.

**Table 7.** Correlation between the thermal–acoustic environment and the path offset.

| | | Sound Type | Temperature Level |
|---|---|---|---|
| Path offset | Correlation coefficient | −0.336 ** | 0.072 |
| | Sig. (two-tailed) | 0.000 | 0.112 |

Note: ** denotes $p$ (two-tailed) < 0.01. Sig. means significance.

The results of multivariate analysis of variance are shown in Table 8. The results indicate that both sound types ($p = 0.000$) and temperature ($p = 0.092$) have significant self-effects on the path offset ($p < 0.1$). As for the interaction between sound and temperature factors, the interaction between sound types and temperature levels ($p = 0.014$) significantly affected the path offset ($p < 0.05$). Therefore, sound and temperature factors both influence the path offset.

**Table 8.** ANOVAs of path offset.

| Source | III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Sound | 8.433 | 2 | 4.216 | 32.712 | 0.000 *** |
| Temperature | 0.618 | 2 | 0.309 | 2.396 | 0.092 * |
| Sound × Temperature | 1.631 | 4 | 0.408 | 3.164 | 0.014 ** |

Note: ***, **, and * denote significance at the 1%, 5%, and 10% level, respectively. Sig. means significance.

The multiple comparisons of mean path offsets under the interaction of sound and temperature are shown in Table 9. For grass-cutting sounds, temperatures are divided into two homogeneous subsets, with low and high heat in one subset, showing significant differences from medium and high heat situations. The path offset was maximum under high-heat conditions. For natural conditions and music playback, there were no significant differences across different temperatures.

**Table 9.** Multiple comparisons of path offset under the influence of the sound type and temperature type.

| Sound Type | Temperature Level | Subset at Alpha = 0.05 | |
|---|---|---|---|
| | | 1 | 2 |
| Grass cutting | Low-heat | 0.13 | |
| | Moderate-heat | 0.18 | 0.18 |
| | High-heat | | 0.35 |
| | Sig. | 0.810 | 0.099 |
| Natural condition | Low-heat | 0.00 | |
| | Moderate-heat | 0.00 | |
| | High-heat | 0.02 | |
| | Sig. | 0.323 | |
| Music | Moderate-heat | −0.20 | |
| | High-heat | −0.12 | |
| | Low-heat | −0.02 | |
| | Sig. | 0.126 | |

Note: Sig. means significance.

The multiple comparisons of mean path offsets under the interaction of temperature and sound are displayed in Table 10. For low-heat conditions, the three sound types were

separated into two homogeneous subsets, where music and natural conditions showed no significant difference, but both differed significantly from grass-cutting conditions, which had the maximum path offset. For moderate heat, there were two homogeneous subsets, with natural conditions and grass cutting in one subset, differing significantly from music conditions, which attracted visitors closer to the source. For high heat, there were also two homogeneous subsets, with music and natural conditions in one subset, differing markedly from grass-cutting conditions, where path offset was most noticeable.

**Table 10.** Multiple comparisons of the path offset under the influence of the sound type and temperature level.

| Temperature Level | Sound Type | Subset at Alpha = 0.05 | |
|---|---|---|---|
| | | 1 | 2 |
| Low-heat | Music | −0.02 | |
| | Natural condition | 0.00 | |
| | Grass cutting | | 0.13 |
| | Sig. | 0.895 | 1.000 |
| Moderate-heat | Music | −0.20 | |
| | Natural condition | | 0.00 |
| | Grass cutting | | 0.18 |
| | Sig. | 1.000 | 0.052 |
| High-heat | Music | −0.12 | |
| | Natural condition | 0.02 | |
| | Grass cutting | | 0.35 |
| | Sig. | 0.312 | 1.000 |

Note: Sig. means significance.

### *3.5. Effects of the Thermal–Acoustic Interaction on Crowd Speed*

#### 3.5.1. Crowd Speed under the Thermal–Acoustic Interaction

Figure 7 shows the crowd speed under the interaction of temperature and sound. Whether or not special sounds were played, the crowd speed under low-heat conditions was lower than under moderate-heat conditions. Under moderate heat, the crowd speed was highest under the grass-cutting sound condition. While under high heat, the crowd speed decreased under the grass-cutting condition.

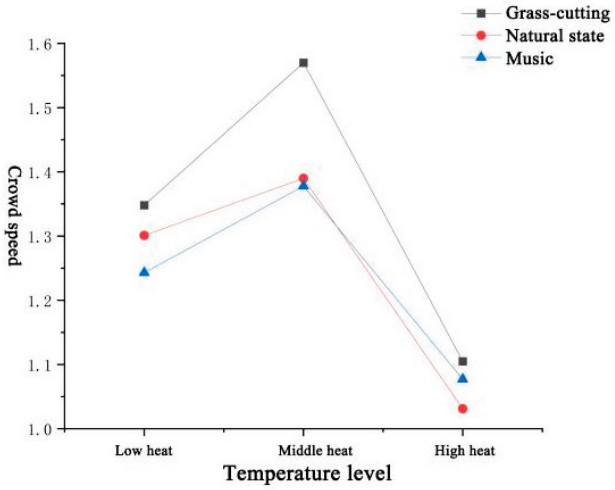



**Figure 7.** Crowd speed under the thermal–acoustic interaction.

Additionally, under low heat, the crowd speed was highest under the grass-cutting condition at 1.348, higher than that under the natural and music conditions. The crowd speed under the natural condition was slightly lower than under the grass-cutting condition at 1.301. The crowd speed was lowest under the music condition at 1.243, somewhat lower

than that under the grass-cutting condition. In comparison, under moderate heat, the crowd speed remained highest under the grass-cutting condition at 1.57, higher than that under both the natural and music conditions. The crowd speed under the natural condition ranked second among the three sound conditions at 1.39. The music condition had the lowest crowd speed at 1.378. Under high heat, the crowd speed was highest under the natural condition at 1.105. The rates under the grass-cutting and music conditions were 1.031 and 1.077, respectively, slightly lower than under the natural condition. However, it should be noted that the crowd speed values decreased under all sound conditions compared to that under the other two temperature conditions.

#### 3.5.2. Analysis of Crowd Speed under the Thermal–Acoustic Interaction

The analysis results show that the correlation coefficient between sound types and crowd speed was −0.177 ($p = 0.000 < 0.01$), and the correlation coefficient between temperature levels and crowd speed was −0.367 ($p = 0.000 < 0.01$), as shown in Table 11. This means that in the urban park environment, pleasant soundscapes can attract tourists to slow down their pace to better appreciate the park experience. Meanwhile, the higher the temperature, the slower the rate. The possible reason is that people do not want to accelerate their movements, which would make them feel hotter. Studies have shown that air temperature and humidity in high-temperature areas negatively impact human physical activity, affecting people's walking speed. In high-temperature areas, people need to consume more energy to maintain body temperature and fluid balance, leading to a reduced walking rate. Additionally, high temperatures can cause fatigue and discomfort, further slowing down the walking rate.

**Table 11.** Correlation between the thermal–acoustic environment and the crowd speed.

| | | Sound Type | Temperature Level |
|---|---|---|---|
| Speed | Correlation coefficient | −0.177 ** | −0.367 ** |
| | Sig. (two-tailed) | 0.000 | 0.000 |

Note: ** denotes $p$ (two-tailed) < 0.01. Sig. means significance.

The results of multivariate analysis of variance are presented in Table 12. The results indicate that both sound types ($p = 0.000$) and temperature ($p = 0.000$) have significant self-effects on the crowd speed ($p < 0.01$). As for the interaction between the temperature and sound factors, the interaction between sound types and temperature levels ($p = 0.006$) significantly affects crowd speed ($p < 0.01$). Therefore, sound and temperature factors both influence the crowd speed.

**Table 12.** ANOVAs of the crowd speed.

| Source | III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Sound | 1.104 | 2 | 0.552 | 15.475 | 0.000 *** |
| Temperature | 10.920 | 2 | 5.460 | 153.035 | 0.000 *** |
| Sound × Temp | 0.517 | 4 | 0.129 | 3.620 | 0.006 *** |

Note: *** denote significance at the 1% level. Sig. means significance.

The multiple comparisons of mean crowd speeds under the interaction of sound and temperature are shown in Table 13. For all sound conditions, the three temperature levels were separated into three homogeneous subsets, with significant differences. It was also observed that medium heat was consistently faster than low and high heat conditions.

The multiple comparisons of mean crowd speeds under the interaction of temperature and sound are displayed in Table 14. For low- and moderate-heat conditions, the three sound types were divided into two homogeneous subsets, where music and natural conditions showed no significant difference, but both differed markedly from grass-cutting

conditions, which had the maximum crowd speed. For high heat, there were no significant differences between sound types.

**Table 13.** Multiple comparisons of the crowd speed under the influence of the sound type and temperature level.

| Sound Type | Temperature Level | Subset at Alpha = 0.05 | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Grass cutting | High-heat | 1.11 | | |
| | Low-heat | | 1.35 | |
| | Moderate-heat | | | 1.57 |
| | Sig. | 1.000 | 1.000 | 1.000 |
| Natural condition | High-heat | 1.03 | | |
| | Low-heat | | 1.30 | |
| | Moderate-heat | | | 1.39 |
| | Sig. | 1.000 | 1.000 | 1.000 |
| Music | High-heat | 1.08 | | |
| | Low-heat | | 1.24 | |
| | Moderate-heat | | | 1.38 |
| | Sig. | 1.000 | 1.000 | 1.000 |

Note: Sig. means significance.

**Table 14.** Multiple comparisons of the crowd speed under the influence of temperature type and sound type.

| Temperature Level | Sound Type | Subset at Alpha = 0.05 | |
|---|---|---|---|
| | | 1 | 2 |
| Low-heat | Music | 1.24 | |
| | Natural condition | 1.30 | 1.30 |
| | Grass cutting | | 1.35 |
| | Sig. | 0.148 | 0.287 |
| Moderate-heat | Music | 1.38 | |
| | Natural condition | 1.39 | |
| | Grass cutting | | 1.57 |
| | Sig. | 0.959 | 1.000 |
| High-heat | Natural condition | 1.03 | |
| | Music | 1.08 | |
| | Grass cutting | 1.11 | |
| | Sig. | 0.053 | |

Note: Sig. means significance.

## 4. Discussion

### *4.1. Interactions of the Thermal and Acoustic Environment on Crowd Behaviours*

Visitors have various purposes in different urban park spaces, which in turn influence crowd behavior differently. This study demonstrates that the thermal–acoustic interaction has a significant impact on crowd behavior, with interactions between sound and varied temperatures of high, medium, and low heat leading to changes in crowd behavior. Therefore, in urban parks, rationally combining specific sounds and temperatures can not only satisfy the usage needs of different functional zones, but also better control visitor flow.

Some urban park spaces require attraction, while others need to guide crowds along proper routes. Research finds that good acoustics in city parks attract crowds. By introducing pleasant natural music, the auditory ambiance of the park can be enhanced. For example, concealed speakers can be installed in the park to play beautiful music or natural sounds, enriching the auditory experience. Meanwhile, the study also indicates that when high temperatures are combined with irritating noise, it can cause discomfort among tourists and lead to their departure. Therefore, the park should suspend noisy operations and provide a quiet space during hot weather. For venues with negative sounds

or thermal factors, like plazas near busy roads, adverse sensory sources should be prioritized for improvements. If the governance effect is limited, positive sounds or temperature regulation should be actively introduced. Previous studies show that people gravitate toward pleasing acoustics [20], further demonstrating the universal appeal of favorable soundscapes regardless of singular or multi-sensory stimuli [51].

Regarding the number of people staying, the study points out that in urban parks, higher temperatures correlate with lower willingness to stay and appreciate the scenery. Without acoustics delivering quality stimulation, instances of staying decrease under high heat. On sound types, park acoustics do not markedly impact attraction, given reasonable temperature ranges. The positive overlapping of sound and temperature can be utilized to increase the willingness to stay, effectively promoting interactions. Adverse sound and thermal factors require appropriate mitigation. For example, to enhance the microclimate of the park, increasing tree shade coverage or providing sunshades can help to alleviate the issue of reduced visiting times for tourists at high temperatures. Past research shows the people favor comfortable thermal settings [52], additionally elucidating the universal appeal of pleasant thermal conditions regardless of single or multi-sensory stimuli [53].

In terms of path offset, the study indicates that in urban parks, pleasant acoustics attract visitors towards sound sources, while unpleasant sounds make people uneasy and repel them. Moreover, sound–temperature interplay also impacts the path offset. Significant differences exist between low and high heat for noises, like grass cutting. Under low and high heat, sound types also differ significantly. Under medium heat, light music markedly differs from other sounds. Therefore, appropriate auditory cues and gradually intensifying or descending temperatures can influence behavior, guiding people along planned routes and avoiding congestion.

Regarding crowd speed, sound and temperature interact to influence velocity based on the results. In urban parks, appealing soundscapes can draw and slow tourists to better enjoy the experience. Meanwhile, higher temperatures are associated with slower paces, likely because people avoid accelerating and overheating [54]. All sound types significantly affect the speed across the three temperature levels. Medium heat is consistently faster than low or high heat. Music and nature do not significantly differ under low or medium heat but substantially differ from grass cutting, where speed is fastest. Under high heat, sound types show no significant differences. By slowing their speed, people can be guided to focus more on the surroundings. Hence, in leisure venues, like urban parks, reducing the crowd speed can enhance the environmental experience [55]. In parks, music or air temperature regulation on paths and plazas can achieve reduced rates when desired.

The findings have an impact on policies and plans aimed at promoting the use of city parks, which plays a crucial role in public well-being. For instance, when there is a need for managing visitor flow in park design and planning, the introduction of specific sounds or adjustments in temperature can influence behavioral tendencies, with certain combinations of sound and temperature reinforcing these effects. Furthermore, different auditory or thermal stimuli in the park environment can have unique effects on crowd behavior. By considering these sensory factors, it becomes possible to accurately predict behaviors in both existing and planned park spaces. Moreover, the use of tailored sounds or the regulation of temperature can mitigate the negative impact of unwanted ambient noises or extreme temperatures on crowd behavior. This analytical approach can be applied to study combinations of different sounds and temperatures, such as addressing noise pollution or tackling excessive heat, to inform decisions on functional zoning, greenery utilization, and government actions related to urban parks.

### *4.2. Shortcomings and Prospects*

This study can be expanded in several directions. The experiment was conducted in the afternoon, and crowd physical conditions and psychological perceptions may differ at various times of day. Moreover, the participants' ages may have also influenced the current results; therefore, similar studies should be carried out at other times during the day in the

future. Additionally, future studies should consider other environmental factors related to bodily perceptions that may impact experimental results.

## 5. Conclusions

This study examines the thermal–acoustic interaction's impact on crowd behavior via covert observations combining archetypal thermal–acoustic factors in urban parks. The principal findings are as follows:

(1) In terms of the number of people, favorable acoustics can attract larger crowds. Stimulating sounds, like grass cutting, reduce the crowd size under high heat. Moreover, excluding adverse noises, urban park soundscapes do not significantly impact visitor attraction across temperatures.
(2) Regarding the number of persons staying, high temperatures reduce sightseeing interest, especially with a suboptimal soundscape, prompting departure. Additionally, apart from hot weather, park acoustics do not markedly influence the stay duration.
(3) With respect to the path offset, the acoustic quality determines visitor proximity to sound sources as shown by the path offset, while significant differences emerged in the path offset for grass cutting at varying temperatures, most prominently under high heat. In contrast, natural sounds and music playback do not significantly impact the path offset across temperatures. Under low heat, music and nature do not differ, but both substantially differ from grass cutting, causing the greatest offset. Under moderate heat, nature and grass cutting are analogous, while music attracts visitors. However, under high heat, music and nature are similar but markedly differ from grass cutting, greatly affecting the path offset.
(4) In terms of crowd speed, appealing soundscapes attract and slow tourists to enjoy the park. Moreover, higher temperatures are associated with slower walking. All sound types significantly affect the speed across the three temperature levels. While in moderate heat, speed is consistently faster than in low or high heat. In contrast, in low and moderate heat, music and nature do not significantly differ but substantially differ from grass cutting, where speed is fastest. However in high heat, sound types do not significantly differ.

**Author Contributions:** Conceptualization, Y.C. and J.D.; methodology, Y.C., J.D. and Z.C.; software, Y.C., S.L., T.L. and Z.C.; validation, Y.C., Z.C., S.L. (Shumeng Lin), X.L., T.L. and S.L. (Shuting Li); formal analysis, Y.C., Z.C., S.L. (Shumeng Lin), X.L., T.L. and S.L. (Shuting Li); investigation, Y.C., Z.C., S.L. (Shumeng Lin), X.L., T.L. and S.L. (Shuting Li); resources, Y.C., S.L. (Shumeng Lin), X.L. and T.L.; data curation, Y.C., X.L., T.L. and S.L. (Shuting Li); writing—original draft preparation, Y.C., Z.C., S.L. (Shumeng Lin), X.L., T.L. and S.L. (Shuting Li); writing—review and editing, Y.C. and S.L. (Shuting Li). All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the (1) Special Project of Wuyishan National Park Research Institute, grant number KJG20009A; (2) Forest Park Engineering Technology Research Center of State Forestry Administration, grant number PTJH15002; (3) Green Urbanization across China and Europe: Collaborative Research on Key technological Advances in Urban Forests, grant number 2021YFE0193200; (4) Horizon 2020 strategic plan: CLEARING HOUSE-Collaborative Learning in Research, Informationsharing, and Governance on How Urban tree-based solutions support Sino-European urban futures, grant number 821242.

**Data Availability Statement:** The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Ma, T.; Sun, S.; Fu, G.; Hall, J.W.; Ni, Y.; He, L.; Yi, J.; Zhao, N.; Du, Y.; Pei, T.; et al. Pollution exacerbates China's water scarcity and its regional inequality. *Nat. Commun.* **2020**, *11*, 650. [CrossRef] [PubMed]
2. Sun, S.; Zheng, X.; Liu, X.; Wang, Z.; Liang, L. Global pattern and drivers of water scarcity research: A combined bibliometric and geographic detector study. *Environ. Monit. Assess.* **2022**, *194*, 523. [CrossRef] [PubMed]

3. Awasthi, A.K.; Li, J.; Koh, L.; Ogunseitan, O.A. Circular economy and electronic waste. *Nat. Electron.* **2019**, *2*, 86–89. [CrossRef]
4. Fucheng, Y.; Jichang, Y.; Yuehong, W.; Dawei, C. Site environmental assessment to an old paint factory in China. *Environ. Monit. Assess.* **2008**, *139*, 93–106.
5. Kastner, J. The new baby boom. *Soap Perfum. Cosmet.* **2016**, *89*, 19.
6. Huang, Y.; Griffin, M.J. The discomfort produced by noise and whole-body vertical vibration presented separately and in combination. *Ergonomics* **2014**, *57*, 1724–1738. [CrossRef]
7. Wang, C.; Geng, L.; Rodríguez-Casallas, J.D. How and when higher climate change risk perception promotes less climate change inaction. *J. Clean. Prod.* **2021**, *321*, 128952. [CrossRef]
8. Shepherd, D.; Welch, D.; Dirks, K.N.; Mathews, R. Exploring the relationship between noise sensitivity, annoyance and Health-Related quality of life in a sample of adults exposed to environmental noise. *Int. J. Environ. Res. Public Health* **2010**, *7*, 3579–3594.
9. King, R.P.; Davis, J.R. Community noise: Health effects and management. *Int. J. Hyg. Environ. Health* **2003**, *206*, 123–131.
10. Selamat, F.E.; Tagusari, J.; Matsui, T. Mapping of transportation noise-induced health risks as an alternative tool for risk communication with local residents. *Appl. Acoust.* **2021**, *178*, 107987.
11. Hong, X.-C.; Liu, J.; Wang, G.-Y. Soundscape in Urban Forests. *Forests* **2022**, *13*, 2056. [CrossRef]
12. Giannaros, T.M.; Melas, D. Study of the urban heat island in a coastal Mediterranean City: The case study of Thessaloniki, Greece. *Atmos. Res.* **2012**, *118*, 103–120. [CrossRef]
13. Yang, B.; Yang, X.; Leung, L.R.; Zhong, S.; Qian, Y.; Zhao, C.; Chen, F.; Zhang, Y.; Qi, J. Modeling the impacts of urbanization on summer thermal comfort: The role of urban land use and anthropogenic heat. *J. Geophys. Res. D Atmos.* **2019**, *124*, 6681–6697.
14. de Souza E Silva, R.; da Silva, R.M.; de Freitas, A.F.; Dos Santos, J.S.; Santos, C.A.G.; de Lima, E.R.V. Thermal comfort conditions at microclimate scale and surface urban heat island in a tropical city: A study on Joao Pessoa city, Brazil. *Int. J. Biometeorol.* **2022**, *66*, 1079–1093. [PubMed]
15. Loures, L.; Santos, R.; Panagopoulos, T. Urban parks and sustainable city Planning-The case of portimão, portugal. *WSEAS Trans. Environ. Dev.* **2007**, *3*, 171–180.
16. Di, L.; Yan, S.; Yue, Y.; Yi, H.; Chengyang, X. Urban park use and self-reported physical, mental, and social health during the COVID-19 pandemic: An on-site survey in Beijing, China. *Urban For. Urban Green.* **2023**, *79*, 127804.
17. Hong, X.-C.; Cheng, S.; Liu, J.; Dang, E.; Wang, J.-B.; Cheng, Y. The Physiological Restorative Role of Soundscape in Different Forest Structures. *Forests* **2022**, *13*, 1920. [CrossRef]
18. Rigolon, A.; Browning, M.; Jennings, V. Inequities in the quality of urban park systems: An environmental justice investigation of cities in the United States. *Landsc. Urban Plan.* **2018**, *178*, 156–169. [CrossRef]
19. Jin, Y.; Jin, H.; Kang, J. Combined effects of the thermal-acoustic environment on subjective evaluations in urban squares. *Build. Environ.* **2020**, *168*, 106517. [CrossRef]
20. Chen, Y.; Liu, F.; Lin, X.; Liu, J.; Chen, Z.; Shi, K.; Li, J.; Dong, J. Combined Effects of the Thermal-Acoustic Environment on Subjective Evaluations in Urban Park Based on Sensory-Walking. *Forests* **2023**, *14*, 1161. [CrossRef]
21. Guo, X.; Liu, J.; Chen, Z.; Hong, X.-C. Harmonious Degree of Sound Sources Influencing Visiting Experience in Kulangsu Scenic Area, China. *Forests* **2023**, *14*, 138. [CrossRef]
22. Menatti, L.; Heft, H. Editorial: Changing Perspectives on Landscape Perception: Seeking Common Ground between the Psychological Sciences and the Humanities. *Front. Psychol.* **2020**, *11*, 159. [CrossRef] [PubMed]
23. Meng, Q.; Kang, J. The influence of crowd density on the sound environment of commercial pedestrian streets. *Sci. Total Environ.* **2015**, *511*, 249–258. [CrossRef]
24. Amsellem, S.; Höchenberger, R.; Ohla, K. Visual–Olfactory Interactions: Bimodal Facilitation and Impact on the Subjective Experience. *Chem. Senses* **2018**, *43*, 329–339. [CrossRef] [PubMed]
25. Pellerin, N.; Candas, V. Combined effects of temperature and noise on human discomfort. *Physiol. Behav.* **2003**, *78*, 99–106. [CrossRef]
26. Pellerin, N.; Candas, V. Effects of steady-state noise and temperature conditions on environmental perception and acceptability. *Indoor Air* **2004**, *14*, 129–136. [CrossRef]
27. Meng, Q.; Kang, J. Effect of sound-related activities on human behaviours and acoustic comfort in urban open spaces. *Sci. Total Environ.* **2016**, *573*, 481–493. [CrossRef]
28. Meng, Q.; Zhao, T.; Kang, J. Influence of Music on the Behaviors of Crowd in Urban Open Public Spaces. *Front. Psychol.* **2018**, *9*, 596. [CrossRef]
29. Weifeng, Y.; Hai, T.K. A model for simulation of crowd behaviour in the evacuation from a smoke-filled compartment. *Physica A* **2011**, *390*, 4210–4218.
30. Xie, H.; Kang, J.; Mills, G.H. Behavior observation of major noise sources in critical care wards. *J. Crit. Care* **2013**, *28*, 1105–1109.
31. Marušić, B.G. Original Article: Analysis of patterns of spatial occupancy in urban open space using behaviour maps and GIS. *Urban Des. Int.* **2011**, *16*, 36–50. [CrossRef]
32. Lepore, F.; Kostara-Konstantinou, E.; Aletta, F.; Astolfi, A. A preliminary investigation about the influence of soundscapes on people's behaviour in an open public space. In *Internoise 2016, Hamburg, 2016*; Institute of Noise Control Engineering: Hamburg, Germany, 2016.

33. Lavia, L.R.; Witchel, H.J.; Kang, J.; Aletta, F. *Preliminary Soundscape Management Model for Added Sound in Public Spaces to Discourage Anti-Social and Support Pro-Social Effects on Public Behaviour, DAGA 2016 Conference, Aachen, 2016*; DAGA: Aachen, Germany, 2016. [CrossRef]
34. Aletta, F.; Lepore, F.; Kostara-Konstantinou, E.; Kang, J.; Astolfi, A. An Experimental Study on the Influence of Soundscapes on People's Behaviour in an Open Public Space. *Appl. Sci.* **2016**, *6*, 276. [CrossRef]
35. Caldwell, C.; Hibbert, S.A. Play that one again: The effect of music tempo on consumer behaviour in a restaurant. *Eur. Adv. Consum. Res.* **1999**, *4*, 58–62.
36. Spangenberg, E.R.W.S.; Crowley, A.E.; Henderson, P.W. Improving the store environment: Do olfactory cues affect evaluations and behaviors? *J. Mark.* **1996**, *60*, 67–80. [CrossRef]
37. Yao, X.; Yu, K.; Zeng, X.; Lin, Y.; Ye, B.; Shen, X.; Liu, J. How can urban parks be planned to mitigate urban heat island effect in "Furnace cities"? An accumulation perspective. *J. Clean. Prod.* **2022**, *330*, 129852. [CrossRef]
38. Li, J.; Huang, Z.; Zheng, D.; Zhao, Y.; Huang, P.; Huang, S.; Fang, W.; Fu, W.; Zhu, Z. Effect of landscape elements on public psychology in urban park waterfront green space: A quantitative study by semantic segmentation. *Forests* **2023**, *14*, 244. [CrossRef]
39. Lavandier, C.; Defréville, B. The contribution of sound source characteristics in the assessment of urban soundscapes. *Acta Acust. United Acust.* **2006**, *92*, 912–921.
40. Jendritzky, G.; De, D.R.; Havenith, G. UTCI—Why another thermal index? *Int. J. Biometeorol.* **2012**, *56*, 421–428. [CrossRef]
41. Blazejczyk, K.; Epstein, Y.; Jendritzky, G.; Staiger, H.; Tinz, B. Comparison of UTCI to selected thermal indices. *Int. J. Biometeorol.* **2012**, *56*, 515–535. [CrossRef]
42. Peter, B.; Dusan, F.; Krzysztof, B.; Ingvar, H.; Gerd, J.; Bernhard, K.; Birger, T.; George, H. Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *Int. J. Biometeorol.* **2012**, *56*, 481–494.
43. Badruddin, I.A.; Hussain, M.K.; Ahmed, N.S.; Kanesan, J.; Mallick, Z. Noise characteristics of grass-trimming machine engines and their effect on operators. *Noise Health* **2009**, *11*, 98–102. [CrossRef] [PubMed]
44. Ma, J.F. The Influence of Different Music Conditions on Drivers' Attention and Hazard Perception. Ph.D. Dissertation, Liaoning Normal University, Dalian, China, 2014.
45. Tao, L. Research on the Adaptation and Application of Music to Running. Ph.D. Dissertation, Zhejiang University of Technology, Hangzhou, China, 2017.
46. Zahorik, P. Assessing auditory distance perception using virtual acoustics. *J. Acoust. Soc. Am.* **2002**, *111*, 1832–1846. [CrossRef] [PubMed]
47. Watzek, K.A.; Ellsworth, J.C. Perceived Scale Accuracy of Computer Visual Simulations. *Landsc. J.* **1994**, *13*, 21–36. [CrossRef]
48. Husain, G.; Thompson, W.F.; Schellenberg, E.G. Effects of Musical Tempo and Mode on Arousal, Mood, and Spatial Abilities. *Music Percept.* **2002**, *20*, 151–171. [CrossRef]
49. Xiao, C.W.; Ye, J.Q.; Esteves, R.M.; Rong, C.M. Using Spearman's correlation coefficients for exploratory data analysis on big dataset. *Concurr. Comput. Pract. Exp.* **2016**, *28*, 3866–3878. [CrossRef]
50. Wang, F.; Huang, G.H.; Fan, Y.; Li, Y.P. Robust Subsampling ANOVA Methods for Sensitivity Analysis of Water Resource and Environmental Models. *Water Resour. Manag.* **2020**, *34*, 3199–3217. [CrossRef]
51. Tokue, Y.; Koga, K.; Nakamura, A.; Osawa, K.; Seki, K.; Imamura, F.; Nishihiro, J. Effects of hearing diverse orthoptera sounds on human psychology. *Urban For. Urban Green.* **2022**, *73*, 127512. [CrossRef]
52. Zhou, L.-Y.; Schmude, J.; Zhai, P.-M.; Wang, Q. Changes in thermal comfortable condition in the Qinghai-Tibet Plateau from 1979 to 2020. *Adv. Clim. Chang. Res.* **2022**, *13*, 666–675. [CrossRef]
53. Medina, D.C.; Delgado, M.G.; Amores, T.R.P.; Toulou, A.; Ramos, J.S.; Domínguez, S.Á. Climatic Control of Urban Spaces Using Natural Cooling Techniques to Achieve Outdoor Thermal Comfort. *Sustainability* **2022**, *14*, 14173. [CrossRef]
54. Melnikov, V.R.; Krzhizhanovskaya, V.V.; Lees, M.H.; Sloot, P.M. The impact of pace of life on pedestrian heat stress: A computational modelling approach. *Environ. Res.* **2020**, *186*, 109397. [CrossRef]
55. Paraskevopoulou, A.T.; Chletsou, M.; Malesios, C. Runners Experience Lower Heart Rate, Increased Speed, and Joy/Calm on Routes with Trees, by the Sea and through Parks: Implications for Climate Change Design. *Sustainability* **2022**, *14*, 16280. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# The Restorative and Contingent Value of Biophilic Indoor Environments in Healthcare Settings

**Yuxiang Lan [1] and Qunyue Liu [1,2,3,*]**

[1] College of Architecture and Urban Planning, Fujian University of Technology, Fuzhou 350118, China; 19912325@fjut.edu.cn
[2] Key Laboratory of New Technology for Construction of Cities in Mountain Area, Ministry of Education, Chongqing University, Chongqing 400045, China
[3] Section for Landscape Architecture and Planning, University of Copenhagen, Frederiksberg C, 1958 Copenhagen, Denmark
* Correspondence: fjlqy@fjut.edu.cn

**Abstract:** During the COVID-19 pandemic, individuals undergoing healthcare-related quarantine often experience heightened anxiety and stress. While biophilic indoor environments have shown potential in reducing stress, their effectiveness within healthcare quarantine settings remains uncertain. Additionally, the economic value associated with implementing biophilic interventions in healthcare environments remains largely unknown. This study aimed to explore the effects of biophilic interventions in indoor quarantine environments on the perceived outcomes of individuals (such as preference, perceived restorativeness, and satisfaction) and their willingness-to-pay (WTP). Participants were asked to imagine themselves in quarantine and were subsequently assigned to one of four indoor rooms, each featuring a different level of biophilic intervention (non-biophilic, low, medium, and high indoor green). Their perceived outcomes and WTP were then evaluated. The findings consistently demonstrated that incorporating biophilic interventions had a significantly positive impact on perceived outcomes and WTP compared with non-biophilic interventions within healthcare quarantine settings. Among the three levels of biophilic intervention, high indoor green spaces had the highest influence, while low indoor green spaces had the lowest. Moreover, perceived restorativeness consistently played a role in influencing WTP across all three biophilic indoor rooms. Further analysis indicated that a medium level of biophilic intervention would be more advantageous and practical in the design of healthcare indoor environments. This study offers valuable insights into both the monetary and nonmonetary values of biophilic interventions in healthcare settings, aiding designers in selecting appropriate biophilic designs to create enhanced restorative indoor environments.

**Keywords:** biophilia; psychological restoration; indoor plants; healthcare settings; willingness-to-pay

**Citation:** Lan, Y.; Liu, Q. The Restorative and Contingent Value of Biophilic Indoor Environments in Healthcare Settings. *Sustainability* **2023**, *15*, 11676. https://doi.org/10.3390/su151511676

Academic Editor: Nikos A. Salingaros

Received: 25 June 2023
Revised: 26 July 2023
Accepted: 26 July 2023
Published: 28 July 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The novel coronavirus disease (COVID-19) broke out at the end of 2019 and has spread to more than 200 countries in the world, resulting to a global public health crisis. Additionally, over 92 million people worldwide had been diagnosed with COVID-19, and around 1,980,000 infected individuals had died from the disease as at 14 January 2021 [1]. In China, the government has taken several control measures since the outbreak of COVID-19, including the ban of mass gatherings, imposing lockdowns on cities, mandatory isolation, and compulsory home reclusion and social distancing. These approaches have been proven to be effective ways of slowing down the spread of COVID-19 and ideally controlling the pandemic. However, these measures and the spread of the disease have also resulted in the occurrence of psychological health problems. Notably, anxiety, depression (16–28%), and stress (8%) were reported to be the most common symptoms during the pandemic [2]. During the pandemic, individuals who had been in close contact with infected patients

or a potentially high-risk environment were required to stay in quarantine for two weeks, at home or at assembly sites across China. In addition, individuals suspected of being infected were required to isolate in healthcare settings. Nonetheless, quarantine can lead to negative psychological effects, including post-traumatic stress symptoms, confusion, and anger [3]. For instance, an online study conducted in Ireland during mass public quarantine (27 March 2020 to 8 June 2020) revealed that there was an increase in the mean levels of participants' depression, anxiety, and stress, with the levels of depression having the highest increase [4]. Notably, previous studies have proposed several interventions to reduce the potential negative impacts of quarantine. These include reducing the quarantine period as much as possible, giving people as much information as possible, and providing adequate supplies, as well as reducing boredom and improving communication [3]. However, little information exists on the influence of living environments on the mental health of individuals kept in quarantine in healthcare settings. Thus, a better understanding of interventions in healthcare settings that alleviate the anxiety and stress resulting from the quarantine is needed in such uncertain circumstances.

Exposure to natural outdoor environments has become a frequently used approach by people in urban areas to relax and reduce stress [5]. In addition, studies have shown that interacting with nature improves health and well-being by restoring attention, reducing stress, and enhancing social cohesion [6–8]. Moreover, a previous study revealed that having a household with a green area was helpful during the quarantine period [9]. However, rapid urbanization across the world has made accessibility to green spaces quite difficult [10]. Worse still, the people who were kept in quarantine for 14 days at healthcare settings spent most of their time indoors, resulting in more separation from natural environments. According to previous research, living environments devoid of nature may act as a "discord", i.e., have a negative effect on health [11], and living in environments with minimal or without plants may result in irritation, hostility, or other negative behaviors [12]. These negative behaviors may particularly be experienced following quarantine due to the COVID-19 pandemic [3] and may further result in increased levels of negative emotions, including fear, disappointment, uncertainty, and stress [13].

Existing research suggests that including nature in indoor environments also confers several benefits, including reducing stress, increasing cognition and emotion, and improving health and well-being [11,14]. Studies on the interior spaces of hospitals also showed that the inclusion of natural sounds and green plants helped reduce mental stress and increase tolerance to pain [15,16]. In addition, Kim et al. [17] found that the inclusion of plants or artificial windows in underground environments could help increase positive perceptions. Employees were also shown to prefer natural construction material in patient rooms [18]. Integrating nature into built environments refers to the concept of biophilic design, which has been considered as a new approach to incorporate the positive experience of nature into indoor environments [19]. Biophilic design stems from the concept of biophilia, which literally means "love of life and living systems" and holds that humans have an innate inclination to nature [20–22]. The deep affinity of humans to nature is rooted in our genetic heritage and is a product of biological evolution [23]. Biophilic design in working and living environments could provide more chances of exposure to natural elements while indoors [24], thus increasing performance at work [25] or the health and well-being of inhabitants [26]. Thus, it is likely that indoor environments with biophilic intervention could help individuals reduce stress and anxiety during quarantine.

There are different attributes of biophilic design, e.g., green plants, long distance, natural view, biomorphic shapes, natural analogues, and 14 patterns, prioritizing the most prominent nature–health relationships in the built environment [14,19,27]. Research has found that plant placement in space [28], geometries [29,30], and natural light, as well as material and patterns [14], have significant influence on the user's satisfaction and health recovery. Out of these, plants are affordable, easily accessible, and more relevant to indoor environments, and they require only small areas of indoor space, such as shelves and desks. In addition, plants have been identified as key biophilic elements that can

be incorporated into indoor environments and are regarded as the most obvious and powerful additions for creating a positive indoor environment [17,31]. Therefore, indoor plants are usually the focus of most studies on biophilic design. Moreover, it was reported that the most noticeable effect of indoor plants on people was their ability to increase positive emotions and reduce stress [32]. For example, the presence of indoor plants was shown to be associated with a reduction in pain, fear, unhappiness, and aggressiveness [33]. Additionally, being in indoor environments with plants was reported to lower levels of stress compared with indoor environments without plants [34,35]. Moreover, having plants at home was reported to be associated with positive emotions while in confinement during the COVID-19 pandemic [36]. Individuals were also reported to prefer working in an office with indoor plants, as they could not only enhance health and well-being but also give higher satisfaction [37,38]. The presence of greenery indoors, which includes the number of houseplants in the home and the proportion of exterior greenery visible from inside, has been shown to significantly enhance the restorative quality of the home environment during the COVID-19 quarantine [39]. Overall, existing evidence highlights the psychological benefits of biophilic design with indoor plants, although little is known about the number of indoor plants that are needed to give these health and well-being outcomes. Furthermore, it is largely unclear how different levels of biophilic design with indoor plants contribute to preference, perceived restorativeness, and satisfaction while in quarantine. In addition, it is not known whether indoor plants have an impact on individuals' willingness-to-pay (WTP) for indoor environments during quarantine in healthcare settings. Research on exploring the effect of a varying quantity of indoor plants on individuals' stress reduction, satisfaction, and WTP is important for both research purposes and government control measurement practice.

Previous studies used a Contingent Valuation Method (CVM) to assess the monetary value of green spaces based on people's willingness-to-pay for use or conservation of urban green spaces [40–42]. Notably, the CVM is commonly used in cost–benefit analysis and environmental impact assessment because it is relatively simple to implement and applies to a wide range of value categories [43]. For instance, Latinopoulos et al. [44] used the CVM to estimate the WTP by local residents for the provision of a new park in the city of Thessaloniki, Greece. Additionally, Majumdar et al. [42] used the CVM to examine tourists' WTP for urban forests in Savannah, Georgia, USA. Moreover, Chen and Qi [40] assessed the recreational use and amenities of the Fuzhou National Forest Park, Fuzhou, China and estimated the monetary value of the Fuzhou National Forest Park to the visitors. The above studies similarly found that a majority of participants were willing to pay for the provision, use, or improvement of urban green spaces. However, all these studies solely focused on estimating the value of outdoor green spaces. Therefore, the economic value of indoor nature remains largely unclear. Furthermore, few studies have been conducted on the economic value of biophilic indoor environments using the CVM.

The CVM uses a questionnaire to obtain people's preference, expressed in monetary terms. In this method, an institutional context is established based on a hypothetical change in the quantity or quality of environmental assets or services. Participants are then asked to give responses on the maximum amount of money they are willing to pay for the hypothetical scenario change (WTP) or the minimum amount of money they are willing to accept to compensate for the change (WTA) [41]. Although the CVM approach is widely used to assess the monetary value of green spaces, Spangenberg and Settele [45] criticized this method, since it does not account for the multifaceted concept of value. Additionally, studies assessing the monetary value of green spaces using CVM often focus on the attached value, without paying enough attention to the underlying value [46]. Moreover, recent research suggested that the CVM, as a monetary valuation approach, should be used along with nonmonetary strategies (e.g., the measurement of individual cognitive attachment to nature) to estimate the value of urban green spaces under various institutional contexts [46,47]. Therefore, the present study combined CVM and nonmonetary approaches to examine this subject.

This study aimed to assess the impact of biophilic indoor intervention in healthcare settings on people's perceived outcomes and their WTP. The results from this study, therefore, provide insights on creating a positive indoor environment for people quarantined in healthcare settings. The study answered the following questions: (1) Do various levels of biophilic indoor environments have different impacts on preference, perceived restorativeness, satisfaction, and WTP? (2) Which level of biophilic intervention is better in improving people's preference, perceived restorativeness, satisfaction, and WTP? (3) Do preference, perceived restorativeness, and satisfaction have an impact on WTP?

## 2. Materials and Methods

### *2.1. Study Design*

The study used a randomized crossover design to investigate differences among participants' ratings of preference, perceived restorativeness, satisfaction, and WTP for rooms with different levels of biophilic indoor designs. This approach could control the potential time-invariant confounding factors and increase statistical power. In addition, participants acted as their own controls, and their ratings were measured repeatedly. All respondents gave their ratings on rooms with varying levels of biophilic indoor interventions, with the order randomized.

### *2.2. Stimuli*

The purpose of this study was to assess the effects of a biophilic indoor design in a healthcare setting. Therefore, a panoramic picture of an actual room, which represented a healthcare room used for quarantine during the pandemic, was selected and used as the base to create the three-dimensional indoor room model. In addition, the three-dimensional indoor room environment was further modified with biophilic elements to create three other versions of indoor rooms (low indoor green, medium indoor green, and high indoor green) with varying levels of the biophilic design intervention. These modifications were based on real indoor environments from an architectural design firm and photos on the Internet. Notably, the low indoor green room focused on adding pot plants on the desk. On the other hand, the medium indoor green room was based on the low indoor green room, although more potted plants were added on the ground. Finally, the living wall was incorporated into the medium indoor green room to make the high indoor green room. Photos of the four indoor rooms (Figure 1) were also presented in the questionnaires to give the respondents an easier time. Furthermore, a link for each indoor room was provided, where a three-dimensional model was present, allowing for a more comprehensive view of the indoor environments in all directions.

### *2.3. Measure*

The questionnaires were divided into three parts, including ratings of perceived outcomes, WTP for the biophilic indoor room, and demographic information. They were developed based on existing guidelines on CVM [43,48] and the valuation of green spaces through monetary and nonmonetary approaches [46]. After receiving explanations on the purpose of the present study, participants were asked to imagine that they were under quarantine for 14 days to complete medical observation due to disease prevention policies. Thereafter, a picture and a link of the biophilic indoor environments were presented to the participants. Additionally, the participants were informed that they would be kept in quarantine in the present room for 14 days, and they could access all the directions of the indoor room via the link. This approach was borrowed from a study by Andrade and Devlin [49], who asked participants to imagine a hospitalization scenario, after which they gave their responses regarding their perception of stress. The approach was also similar to that used in previous studies on restorativeness, where respondents were asked to imagine themselves in a fatigued mind before viewing nature, after which they provided their restorative perceptions [50,51]. Moreover, this approach has been validated to accurately simulate real environments [52,53].

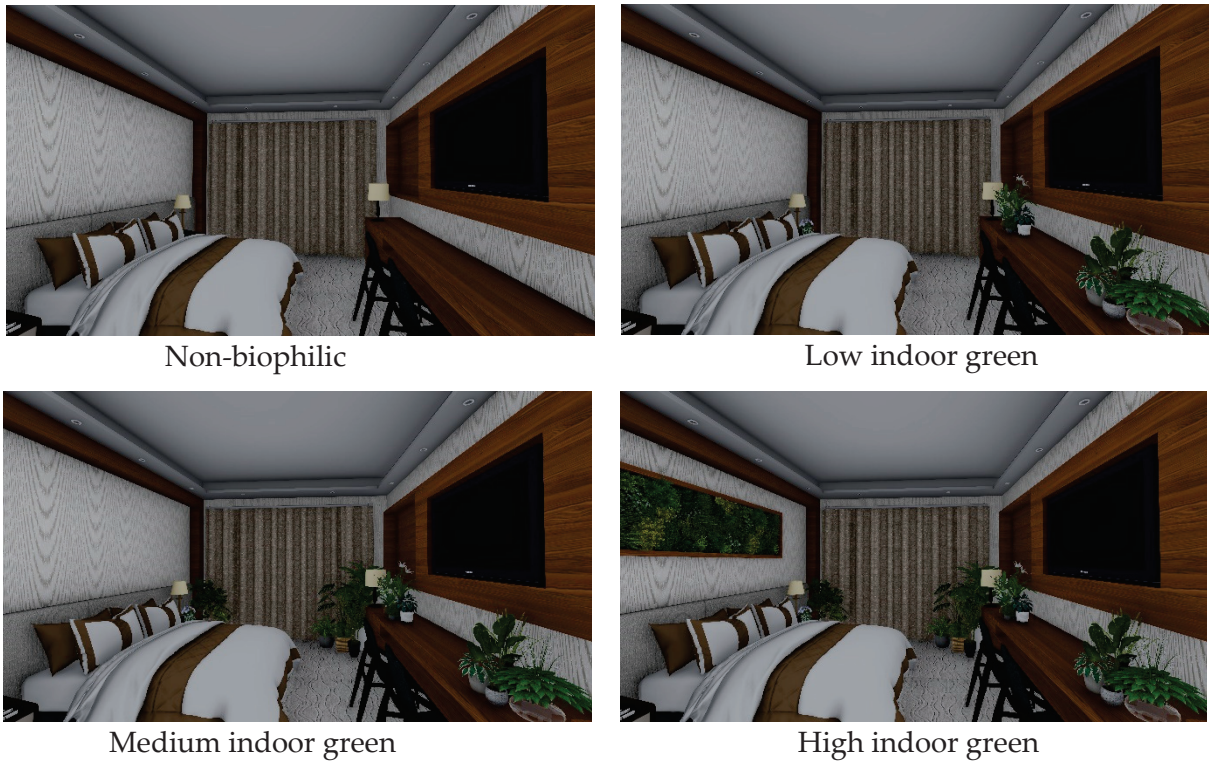



**Figure 1.** The four indoor rooms layouts.

To alleviate fatigue in respondents and increase their willingness to participate in this study, the three outcomes, i.e., preference, perceived restorativeness, and satisfaction, were measured using only one item, respectively. The single-item measure of preference, perceived restorativeness, and satisfaction has previously been used by studies on restorative benefits and satisfaction from green spaces [50,54,55]. In addition, the three variables were measured using the following questions: "How much do you agree that you like the present indoor room environment?", "Overall, how much do you agree that the present indoor room environment would help to facilitate your psychological restoration during the quarantine?", and "How much do you agree that you are satisfied with the present indoor room environment?". The participants gave their responses for these items on a 7-point Likert scale anchored at "1 = Not at all" and "7 = Very much so". The three variables were also treated as nonmonetary approaches to estimate the value of indoor green environments and used to assess their association with WTP.

The second part involved assessing the respondents' WTP by taking them through the three biophilic indoor rooms, and the CVM was applied in the process. It is noteworthy that CVM has been criticized due to methodological flaws and the potential pitfalls involve hypothetical bias, elicitation and starting point biases, and sequencing and information effects, as well as failure of the scope test. However, these biases can be overcome through careful study design and implementation [56]. To address these potential biases, several measures were implemented in the present study, including presenting the four scenarios with pictures and using a three-dimensional model to improve the intelligibility. We also used a randomized order and payment cards, which respondents were familiar with, as they already existed. Moreover, pictures of both non-biophilic and the proposed biophilic indoor rooms were included in the questionnaires, with a brief description of the comparison between these two indoor room environments (e.g., "Compared to the indoor room with a non-biophilic design, the low indoor green room includes potted plants on the tables."). Following this, respondents were asked whether they were willing to pay the extra fee for the specific biophilic indoor room compared with the one with a non-biophilic design. If the response was positive, a payment card with different listed amounts (0, 10, 20, 30, 40,

50, 60, 70, 80, 90, and 100 RMB; USD = CNY 6.43) was shown, and participants were asked to circle the highest amount they would be willing to pay. On the other hand, participants who were unwilling to pay were asked to give their reasons for the same. Finally, the third part focused on participants' demographic information, which included gender, age group, level of education, monthly income, and area of residence.

### *2.4. Survey Procedure and Participants*

The survey was conducted online through Wechat v7.0.20, QQ v9.2.3, email, and Sina Weibo v10.0.0 from May to November 2020. Notably, the online survey was cheaper and could easily be accessed by participants, particularly during the pandemic. Online surveys were also used in previous studies [54,57], and their validity was proven by Roth [58]. In addition, the study applied a snowball sampling method to recruit participants, and the survey was initiated by twenty graduates from different parts of China. Moreover, over six hundred Chinese adults from different parts of China with a wide demographic range filled out the questionnaire. The participants were first required to read the explanation and instructions, after which they watched an indoor room scenario and then responded to the questions. The four scenarios were presented randomly. Finally, participants were asked to give their demographic information. It took about eight minutes to complete a questionnaire.

A total of 632 responses were obtained. After excluding invalid responses (e.g., omission of some questions or providing the same response for most of the questions), 498 responses were left, including 244 responses from males and 254 from females. The majority of the participants were between 18 to 29 years of age (38.76%), and the second largest number of participants were between 30–39 years old (36.95%). Additionally, most of the participants had a bachelor's degree (78.71%), with a smaller representation of other education backgrounds. With regards to occupation, 29.32% were company staff, while 7.4% were official or university employees. Moreover, around sixty percent of the participants' monthly income was less than CNY 5000, and 17.6% had a monthly income of more than CNY 10,000.

### *2.5. Data Processing*

This study used ANOVA to examine the effects of the indoor environmental conditions (non-biophilic, low indoor green, medium indoor green, and high indoor green) on the outcomes (preference, perceived restorativeness, and satisfaction). If significant differences were obtained, post hoc comparisons were made using Tukey's Honestly Significant Difference (HSD) to ascertain where the differences occurred. Additionally, the nonparametric Kruskal–Wallis test was employed to examine whether respondents varied in their WTP for the three biophilic indoor room environments. Before conducting this analysis, protest zeros were detected and excluded from further analysis, since their zero WTP responses did not reveal their real WTP. Notably, protest zero respondents were those who had a positive WTP higher than zero but refused to pay due to either the CVM scenario or disagreeing with the payment vehicle [59]. In the present study, the following reasons as to why participants were unable to pay were identified as protest zeros: "I cannot afford extra room fees", "The indoor plants should be supplied freely", "The healthcare indoor room should be decorated with indoor plants", "Too much indoor greens make me feel uneasy", and "It is not worth paying for a few potted plants". On the other hand, true zero responses included such answers as "I do not like indoor plants" and "I do not care about the indoor green environments" and were separated from the protest zero responses. Finally, an interval regression analysis was performed to investigate the effect of demographic variables and the measured outcome variables on WTP. The method used the interval between the highest amount the participants were willing to pay and the next largest amount, supposing that respondents' real WTP lay somewhere between the two amounts. All the analyses were conducted using SPSS 24 and Stata 16.

## 3. Results

### *3.1. Comparison of Preference, Perceived Restorativeness, and Satisfaction among Different Biophilic Design Interventions*

Descriptive statistics of the ratings of preference, perceived restorativeness, and satisfaction from each room are presented in Table 1. Rooms with the most indoor greens had the highest ratings of preference, restorativeness, and satisfaction. In addition, the original room without any biophilic design intervention obtained the lowest ratings of preference, restorativeness, and satisfaction. Bivariate correlation analysis also showed that the average ratings were positively correlated with the intensity of biophilic intervention (preference: r = 0.312, $p < 0.001$; restorativeness: r = 0.303, $p < 0.001$; satisfaction: r = 0.325, $p < 0.001$, r indicated Spearman's rho). Additionally, the results from ANOVA revealed that the average ratings of preference, restorativeness, and satisfaction were significantly different across the four images (Table 1). Furthermore, the results from post hoc comparisons revealed significant differences between any two biophilic interventions, except for between the high indoor green and medium indoor green rooms (Table 2).

**Table 1.** Descriptive results of the ratings of preference, perceived restorativeness, and satisfaction from each indoor room.

| | **Preference** | | | **Perceived Restorativeness** | | | **Satisfaction** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **95% CI** | **Mean** | **SD** | **95% CI** | **Mean** | **SD** | **95% CI** |
| Original | 4.02 | 1.14 | 3.92 to 4.12 | 3.99 | 1.34 | 3.88 to 4.11 | 4.00 | 1.13 | 3.90 to 4.10 |
| Low indoor green | 4.53 | 1.02 | 4.44 to 4.62 | 4.61 | 1.15 | 4.51 to 4.71 | 4.42 | 1.06 | 4.33 to 4.52 |
| Medium indoor green | 4.83 | 1.12 | 4.73 to 4.93 | 4.86 | 1.20 | 4.76 to 4.97 | 4.85 | 1.10 | 4.75 to 4.95 |
| High indoor green | 4.98 | 1.31 | 4.87 to 5.10 | 5.05 | 1.27 | 4.94 to 5.17 | 4.98 | 1.30 | 4.86 to 5.09 |
| | F (3,1988) = 68.281, $p < 0.001$ | | | F (3,1988) = 68.513, $p < 0.001$ | | | F (3,1988) = 74.299, $p < 0.001$ | | |

**Table 2.** Post hoc comparisons of preference, perceived restorativeness and preference between any two rooms.

| **I** | **J** | **Preference** | | **Perceived Restorativeness** | | **Satisfaction** | |
|---|---|---|---|---|---|---|---|
| | | **MD** | **95% CI** | **MD** | **95% CI** | **MD** | **95% CI** |
| High indoor green | Non-biophilic | 0.97 *** | 0.78 to 1.15 | 1.06 *** | 0.86 to 1.26 | 0.98 *** | 0.79 to 1.17 |
| | Low indoor green | 0.45 *** | 0.26 to 0.64 | 0.44 *** | 0.24 to 0.65 | 0.55 *** | 0.37 to 0.74 |
| | Medium indoor green | 0.15 | −0.04 to 0.34 | 0.19 | −0.01 to 0.39 | 0.13 | −0.06 to 0.32 |
| Medium indoor green | Non-biophilic | 0.82 *** | 0.63 to 1.00 | 0.87 *** | 0.67 to 1.07 | 0.85 *** | 0.66 to 1.04 |
| | Low indoor green | 0.30 *** | 0.12 to 0.49 | 0.25 ** | 0.05 to 0.46 | 0.43 *** | 0.24 to 0.61 |
| Low indoor green | Non-biophilic | 0.51 *** | 0.33 to 0.70 | 0.62 *** | 0.41 to 0.82 | 0.43 *** | 0.24 to 0.61 |

Note: I and J were participants' mean ratings for a picture with a particular intensity of biophilic design. MD: Mean difference (I-J), CI: Confidence interval, **: $p \leq 0.01$, ***: $p \leq 0.001$.

### *3.2. Marginal Effects of Biophilic Design Intensity on Preference, Restorativeness, and Satisfaction*

The marginal effects of the three biophilic interventions were calculated to ascertain which biophilic design had more power to improve the measured outcomes. The results in Figure 2 show that the marginal effects on preference and restorativeness decreased with an increase in the level of biophilic intervention. Additionally, the marginal effects on satisfaction of the medium indoor green (0.43) design were equal to those of low indoor green (0.43) but higher than those of high indoor green (0.13). These results therefore suggest that the low indoor green design had much more power to improve participants' ratings of preference, restorativeness, and satisfaction, while the high indoor green had the least power.

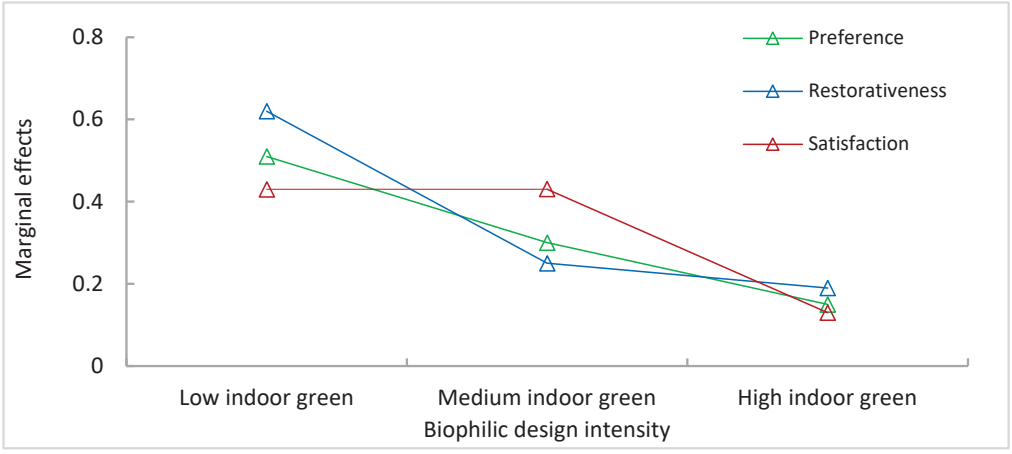



**Figure 2.** The average marginal effects of three biophilic design interventions on measured outcomes.

### *3.3. Comparison of WTP for Different Design Intensities*

Table 3 shows the distribution of respondents with positive and zero WTP for the three rooms with different levels of biophilic designs. Over 85% of respondents were willing to pay for all three rooms with different levels of biophilic interventions, with small differences between the rooms. Among those with zero WTP for the three rooms, only a few (less than 10%) were protest zeros. In addition, the medium indoor green room had the least number of total zeros and protest zeros, while the high indoor green room had the most. With regards to the reason for protesting, respondents protesting the low indoor green mostly reported that there was no need to spend more for only a few potted plants. On the other hand, respondents protesting the medium indoor green room stated that too much indoor greenery made them feel uncomfortable. Finally, all the respondents that protested the high indoor green room similarly said that too much indoor greenery, especially on the wall, made them feel frightened and uncomfortable. Moreover, all the protest responses were recorded, and the real mean WTP for the three rooms with biophilic designs was calculated. As a result, the real mean WTP for the low indoor green, medium indoor green, and high indoor green rooms was CNY 25.68, CNY 32.14, and CNY 36.21, respectively.

**Table 3.** Number and percentage of respondents with positive and zero WTP along with the numbers of protest and real zeroes for the three rooms. N = 498 for each room.

| | **Low Indoor Green (%)** | **Medium Indoor Green (%)** | **High Indoor Green (%)** |
|---|---|---|---|
| Number of respondents with WTP > 0 (percentage of the total sample) | 425 (85.34) | 446 (89.56) | 438 (87.95) |
| Number of the total zeros (percentage of the total sample) | 73 (14.66) | 52 (10.44) | 60 (12.05) |
| Number of protest zeros (percentage of the total zeroes) | 14 (19.18) | 12 (23.08) | 18 (30) |
| Number of real zeroes (percentage of the total zeroes) | 59 (80.82) | 40 (76.92) | 42 (70) |

Results from the Kruskal–Wallis test (Table 4) further revealed that the mean WTP of all the participants was significantly different ($\chi 2(2) = 38.35$, $p < 0.001$). Moreover, post hoc comparisons indicated that the participants' WTP for the medium indoor green and high indoor green rooms was significantly higher than that of the low indoor green room. Although the participants' WTP for the high indoor green room was higher than that of the medium indoor green room, the difference was significant.

**Table 4.** The Kruskal-Wallis Test results for WTP.

| Respondents | N | Chi-Square | df | Mean Rank | | | *p* | Real Mean Values | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Low | Medium | High | | Low | Medium | High |
| Total | 1450 | 38.347 | 2 | 634.96 | 746.19 | 795.85 | <0.001 | 25.68 | 32.14 | 36.21 |

### *3.4. Factors Affecting the Willingness-to-Pay for Biophilic Indoor Design*

Table 5 shows the interval regression results for the three rooms with different levels of biophilic interventions. The results reveal a significant correlation between satisfaction and WTP for the high indoor green room and between restorativeness and WTP for all three rooms. This suggested that if the respondents were more satisfied with the high indoor green room, they were more likely to pay extra room fees. The results also show that their perceived restorativeness on the three rooms positively influenced their WTP. Additionally, the coefficients of education in the low indoor green room and income in the low and high indoor green rooms were significantly correlated with WTP. This indicated that participants with a higher income were more willing to pay an extra fee for the low and high indoor green rooms. On the other hand, participants without college education were more willing to pay an extra fee for the indoor green rooms. All the other variables were, however, not related to WTP for the three rooms with different levels of biophilic designs.

**Table 5.** Interval regression results for WTP for the three levels of biophilic design.

| Variable | Low Indoor Green (N = 484) | | Medium Indoor Green (N = 486) | | High Indoor Green (N = 480) | |
|---|---|---|---|---|---|---|
| | Coef. | Std. Err | Coef. | Std. Err | Coef. | Std. Err |
| Preference | 2.60 | 1.38 | 3.06 | 1.60 | 3.05 | 1.71 |
| Satisfaction | 2.48 | 1.41 | 1.41 | 1.54 | 3.82 * | 1.76 |
| Restorativeness | 2.23 * | 1.10 | 4.85 *** | 1.41 | 3.67 ** | 1.39 |
| Gender | 0.45 | 1.95 | 1.63 | 2.11 | 1.10 | 2.28 |
| Age_dum1 | −2.06 | 3.54 | −0.42 | 3.82 | −2.66 | 4.15 |
| Age_dum2 | 0.64 | 3.48 | 0.35 | 3.78 | 0.49 | 4.07 |
| Age_dum3 | - | - | - | - | - | - |
| Edu_dum | −5.44 * | 2.42 | −4.57 | 2.61 | −3.76 | 2.83 |
| Income_dum1 | −7.89 ** | 2.97 | −5.69 | 3.28 | −7.44 ** | 3.59 |
| Income_dum2 | −4.74 | 3.16 | −6.24 | 3.46 | −7.21 | 3.77 |
| Income_dum3 | −0.29 | 3.08 | 0.05 | 3.33 | −0.35 | 3.63 |
| Income_dum4 | - | - | - | - | - | - |
| Constant | 6.06 | 6.73 | −2.09 | 7.52 | −4.32 | 7.61 |
| Sigma | 20.94 | 0.69 | 22.79 | 0.74 | 24.54 | 0.80 |
| Log likelihood | −1048.83 | | −1093.81 | | −1115.36 | |

Note: Gender = 1 if the respondent was male or = 0 if otherwise; Age_dum1 = 1 if the respondents' age $\leq$ 30 or = 0 if otherwise, Age_dum2 = 1 if the age of respondents > 30 and $\leq$50 or = 0 if otherwise; Age_dum3 = 1 if the respondents' age > 50 or = 0 if otherwise; Edu_dum = 1 if the highest level of education achieved by respondents was higher than college or = 0 if otherwise; Income_dum1 = 1 if the respondents' monthly income was lower than CNY 3000 or = 0 if otherwise; Income_dum2 = 1 if CNY 3000 $\leq$ the respondents' monthly income <CNY 5000 or = 0 if otherwise; Income_dum3 = 1 if CNY 5000 $\leq$ the respondents' monthly income <CNY 10,000 or = 0 if otherwise; Income_dum4 = 1 if CNY 10,000 $\leq$ the respondents' monthly income or = 0 if otherwise. *: $p \leq 0.05$, **: $p \leq 0.01$, ***: $p \leq 0.001$.

## 4. Discussion

### *4.1. Biophilic Indoor Intervention in Relation to Perceived Outcomes and WTP*

Previous studies showed that biophilic indoor environments are beneficial in reducing stress and anxiety [14,32,60] and influencing preference [61] as well as satisfaction [62]. In addition, indoor spaces with plants are thought to have a more restorative potential [63]. The present study showed that biophilic intervention with indoor plants in healthcare setting rooms resulted in higher preference, perceived restorativeness, and satisfaction, corroborating previous findings. The health benefits of indoor nature have been investigated in various settings, including a hospitalization setting, a work office scenario, a home

setup while in confinement during the COVID-19 pandemic [36,49,64], and a healthcare room scenario in the present study. All these studies confirmed the positive effects of indoor plants on psychological restoration or affective response. Therefore, these findings further support the biophilic hypothesis, which posits that humans have an inclination to nature [21,22]. Conversely, this also confirmed that the approach used in this study, in which participants were asked to imagine being quarantined in a healthcare setting indoor room, was valid.

Suppakittpaisarn et al. [65] conducted a survey on the levels of vegetation density in green infrastructure in relation to landscape preference. Their study revealed a power-curve relationship between tree density and preference and understory vegetation density and preference. Additionally, Jiang et al. [66] explored the amount of tree cover associated with stress reduction. Their findings showed that there was an increase in stress recovery with an increase in tree cover from 1.7% to 24%. However, recovery remained constant when the tree cover increased from 24% to 34% and slowed down when the tree cover was above 34%, indicating a quadratic relationship between tree cover and stress recovery. The present study similarly showed that the participants' ratings of preference, restorativeness, and satisfaction towards the indoor rooms increased from the original room without plants to the room with high indoor greens. There was also a decrease in the marginal effect of the biophilic design (except satisfaction). Moreover, there was no significant difference between the high indoor green and medium indoor green rooms, although the participants' preference, perceived restorativeness, and satisfaction were the highest towards the high indoor green room. Notably, some protest zeros reported that they were not willing to pay, since the room with high indoor greens made them feel uneasy. A previous study on preference and intensity of landscape design (defined as "the amount of the original landscape changed and the degree of artificiality of added elements to the landscape by design) showed that a moderate design had a better marginal effect on promoting aesthetic preference. The study, therefore, recommended the moderate designs should be implemented [57]. Additionally, Pérez-Urrestarazu et al. [36] reported that a few indoor plants rather than a high number of plants, placed in strategic positions at home, were preferred. Furthermore, Chiang et al. [67] showed that a high density of vegetation was associated with better attention restoration effects, although a medium density of vegetation was more preferred. Rooms with a high number of indoor greens were also shown to be more likely to result in overdesigning [68]. The above findings, therefore, suggest that a room with a moderate number of indoor greens may be more helpful in improving preference, psychological restoration, and satisfaction.

Additionally, the results show that participants were willing to pay for all three biophilic indoor environments, supporting previous findings that rooms with natural scenic views were more expensive [69]. Moreover, participants had more WTP for the high indoor green room. However, there was no significant difference between the WTP for high indoor green and medium indoor green rooms. This may further indicate that a medium indoor green room is more suitable.

### *4.2. Perceived Outcome Variables in Relation to WTP*

A previous study examined the restorative experience triggered by empowerment features in augmented reality in relation to the willingness of online tourists to pay a price premium during the prepurchase phase. The results indicate that generating a restorative experience resulted in a higher willingness to pay [70]. The present study similarly showed that the perceived restorativeness of biophilic indoor room environments was positively associated with WTP in all three scenarios. The positive relationship between perceived restorativeness and WTP was also shown by previous studies on perceived restorativeness and attitudes or behaviors. For instance, Barbiero and Berto [71] proposed that perceived restorativeness improved individuals' environmental concerns and further resulted in a proenvironmental behavior. In addition, Hartig et al. [72] reported that perceptions of restorative qualities predicted 23% of the differences in ecological behavior. Moreover,

perceived restorativeness was shown to play a mediating role between perceived bird biodiversity and emotional well-being, as well as in perceived naturalness in emotional well-being [73]. Given that participants were under an imagined quarantine situation, it is likely that people attached more importance to health-related problems and their well-being, changing their attitude or behavior towards biophilic indoor environments. Therefore, biophilic indoor environments may elicit higher perceived restorativeness, further resulting in a higher willingness to pay. Additionally, it should be noted that the effect of perceived restorativeness on WTP for biophilic indoor room environments varied according to different scenarios. The highest positive coefficient between perceived restorativeness and WTP was observed in rooms with medium indoor greens. This suggested that participants' perceived restorativeness plays a stronger role in medium indoor green environments compared with the other two biophilic indoor rooms. This is reasonable, because no other variables were found to be associated with the WTP for a high indoor green room. This may also indicate that rooms with medium indoor greens were more preferred by the participants, since their gender, age, education, and income had no correlation with WTP.

In contrast, the results show that a higher preference for biophilic indoor environments did not translate to a higher WTP in all the three scenarios. Although previous studies showed a significant relationship between preference and WTP [74], this may not apply to the present study, since an imagined quarantine scenario may have caused the respondents to put more focus on psychological restoration rather than their preference. In addition, the significant positive contribution of perceived restorativeness on WTP in all three biophilic rooms supports this suggestion. Moreover, satisfaction and perceived restoration were found to have a positive effect on the WTP for high indoor green environments. This was in line with previous findings, which showed that respondents' WTP was significantly associated with their satisfaction with forest park facilities and services [40]. This also supports the idea that WTP represents an attitude rather than economic preference [75,76]. It is therefore possible that in a quarantine situation, respondents pay more attention to the restorative benefits of biophilic indoor environments rather than their preference or satisfaction. This is because preference was not associated with WTP, while satisfaction was only correlated with WTP for high indoor green environments. It is also noteworthy that gender and age were not related to WTP for the three rooms with different levels of biophilic interventions. This indicated that males and females, as well as participants across different age groups, had a similar WTP for biophilic indoor environments. The results further highlight the positive effects of biophilic indoor environments on the general public.

### *4.3. Practical Application*

The results from the present study have important implications. Although several factors are involved, such as location, distance, and price, the indoor room environments should be considered by the government when determining a healthcare setting for quarantine. Additionally, indoor rooms with biophilic interventions should be treated as a priority when the other conditions are similar. Moreover, biophilic elements, e.g., indoor plants, should be added into the indoor room environments of the healthcare settings. Generally, providing moderate amounts of indoor plants would be the best alternative. However, the characteristics of each individual should also be taken into account. In addition, information on the benefits of using indoor plants to alleviate stress, anxiety, or other related symptoms should be made easily available to people in quarantine and the general public. This will in turn help the public increase their knowledge on coping with the negative effects of the pandemic and help them go through stressful events. For healthcare setting managers, decorating indoor room environments with biophilic elements, particularly with indoor plants, could help improve the satisfaction of their guests, and this may help them benefit more. Furthermore, a medium level of biophilic intervention would be necessary to enhance stress recovery and avoid overdesigning. Determining a moderate biophilic intervention can indeed be challenging, but a thoughtful approach that considers plant

selection, plant density, green elements distribution, wall and floor coverage, and user feedbacks, along with comparisons among different indoor design proposals, can help identify the most suitable option. By carefully evaluating these aspects, designers can create a balanced and appealing green space that aligns with the needs and preferences of the intended users.

### *4.4. Limitations and Future Work*

Although the present study provides some eye-opening findings, it has some limitations. First, following a previous study [50,54,55] and given the time limitation, the current study only used one item to measure respondents' ratings of preference, perceived restorativeness, and satisfaction, which may have resulted in bias. Future studies should therefore adopt a more comprehensive method to measure these outcome variables. Second, the study employed an online survey and focused on psychological restoration and therefore did not measure physiological indicators, such as variability in heart rate, heart rate, blood pressure, and skin conductance. This means that it was not possible to analyze the impact of different biophilic interventions on physiological state. An experimental study that replicates the stimuli and combines a subjective and objective approach to measure psychological and physiological indicators would make it possible to compare both psychological and physiological responses. Third, the study mainly focused on the biophilic elements of indoor plants. Future studies should therefore take into account other biophilic elements like natural analogues, symmetries, fractals, colors, and water, as well as natural light, and explore how to integrate these elements in the design process. This could lead to a better level of psychological and physiological restoration.

## 5. Conclusions

This study investigated the effect of different biophilic interventions in healthcare setting indoor room environments on people's preference, perceived restorativeness, satisfaction, and WTP under an imagined quarantine situation. The findings generally suggested that rooms with biophilic intervention had larger effects on preference, perceived restorativeness, satisfaction, and WTP compared with those with non-biophilic interventions. Additionally, the effects differed among the three different levels of biophilic intervention, with the high indoor green environment having the highest effect and the low indoor green setup having the lowest. Moreover, perceived restorativeness consistently contributed to WTP across the three biophilic indoor rooms. The study used CVM and measured perceived outcomes to quantify the monetary and nonmonetary values attached to biophilic interventions in healthcare setting indoor room environments. This, therefore, provided new insights on the values of biophilic intervention in indoor environments. The results also show that a medium level of biophilic intervention may be more useful for psychological restoration and should be recommended for practice. This can help designers in selecting proper biophilic interventions to create better indoor restorative environments. Given that the present study was conducted in China, similar studies involving respondents from other parts of the world with different cultural backgrounds could help validate the present findings and conclusions.

**Author Contributions:** Conceptualization, Y.L. and Q.L.; methodology, Y.L.; software, Y.L.; validation, Y.L.; formal analysis, Y.L.; investigation, Y.L.; data curation, Y.L.; writing—original draft preparation, Y.L.; writing—review and editing, Q.L.; supervision, Q.L.; project administration, Q.L.; funding acquisition, Q.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Key Laboratory of New Technology for Construction of Cities in Mountain Area, Ministry of Education, Chongqing University, grant number LNTCCMA-20220103, the Natural Science Foundation of Fujian Province, China, grant number 2023J05193, Fujian Provincial Department of Education, grant number JAT220220 and FBJG20210001.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Data is available from the first author on reasonable request.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. Dong, E.; Du, H.; Gardner, L. An interactive web-based dashboard to track COVID-19 in real time. *Lancet Infect. Dis.* **2020**, *20*, 533–534. [CrossRef] [PubMed]
2. Rajkumar, R.P. COVID-19 and mental health: A review of the existing literature. *Asian J. Psychiatry* **2020**, *52*, 102066. [CrossRef] [PubMed]
3. Brooks, S.K.; Webster, R.K.; Smith, L.E.; Woodland, L.; Wessely, S.; Greenberg, N.; Rubin, G.J. The psychological impact of quarantine and how to reduce it: Rapid review of the evidence. *Lancet* **2020**, *395*, 912–920. [CrossRef] [PubMed]
4. Burke, T.; Berry, A.; Taylor, L.K.; Stafford, O.; Murphy, E.; Shevlin, M.; McHugh, L.; Carr, A. Increased psychological distress during COVID-19 and quarantine in Ireland: A national survey. *J. Clin. Med.* **2020**, *9*, 3481.
5. Hartig, T.; Kahn, P.H. Living in cities, naturally. *Science* **2016**, *352*, 938. [CrossRef]
6. Hartig, T.; Mitchell, R.; De Vries, S.; Frumkin, H. Nature and health. *Annu. Rev. Publ. Health* **2014**, *35*, 207–228. [CrossRef]
7. Markevych, I.; Schoierer, J.; Hartig, T.; Chudnovsky, A.; Hystad, P.; Dzhambov, A.M.; Vries, D.S.; Triguero-Mas, M.; Brauer, M.; Nieuwenhuijsen, M.J.; et al. Exploring pathways linking greenspace to health: Theoretical and methodological guidance. *Environ. Res.* **2017**, *158*, 301–317.
8. Tyrväinen, L.; Ojala, A.; Korpela, K.; Lanki, T.; Tsunetsugu, Y.; Kagawa, T. The influence of urban green environments on stress relief measures: A field experiment. *J. Environ. Psychol.* **2014**, *38*, 1–9. [CrossRef]
9. Bezerra, A.C.V.; Silva, C.E.M.D.; Soares, F.R.G.; Silva, J.A.M.D. Factors associated with people's behavior in social isolation during the COVID-19 pandemic. *Cienc. Saude Coletiva* **2020**, *25*, 2411–2421. [CrossRef]
10. United Nations. *World Population Prospects*; United Nations: New York, NY, USA, 2018.
11. Aerts, R.; Honnay, O.; Van Nieuwenhuyse, A. Biodiversity and human health: Mechanisms and evidence of the positive health effects of diversity in nature and green spaces. *Br. Med. Bull.* **2018**, *127*, 5–22. [CrossRef]
12. Mouratidis, K. Urban planning and quality of life: A review of pathways linking the built environment to subjective well-being. *Cities* **2021**, *115*, 103229.
13. Xiao, H.; Zhang, Y.; Kong, D.; Li, S.; Yang, N. Social capital and sleep quality in individuals who self-isolated for 14 days during the coronavirus disease 2019 (COVID-19) outbreak in January 2020 in China. *Med. Sci. Monit.* **2020**, *26*, e923921. [CrossRef] [PubMed]
14. Yin, J.; Yuan, J.; Arfaei, N.; Catalano, P.J.; Allen, J.G.; Spengler, J.D. Effects of biophilic indoor environment on stress and anxiety recovery: A between-subjects experiment in virtual reality. *Environ. Int.* **2020**, *136*, 105427. [PubMed]
15. Martin, L.; White, M.P.; Hunt, A.; Richardson, M.; Pahl, S.; Burt, J. Nature contact, nature connectedness and associations with health, wellbeing and pro-environmental behaviours. *J. Environ. Psychol.* **2020**, *68*, 101389. [CrossRef]
16. Zhong, W.; Schröder, T.; Bekkering, J. Biophilic design in architecture and its contributions to health, well-being, and sustainability: A critical review. *Front. Archit. Res.* **2022**, *11*, 114–141. [CrossRef]
17. Kim, J.; Cha, S.H.; Koo, C.; Tang, S.K. The effects of indoor plants and articial windows in an underground environment. *Build. Environ.* **2018**, *138*, 53–62. [CrossRef]
18. Nyrud, A.Q.; Bringslimark, T.; Bysheim, K. Benefits from wood interior in a hospital room: A preference study. *Archit. Sci. Rev.* **2013**, *57*, 125–131. [CrossRef]
19. Kellert, S.R. Dimensions, elements, and attributes of biophilic design. In *Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life*; John Wiley: Hoboken, NJ, USA, 2008; pp. 3–19.
20. Kellert, S.R. *Nature by Design: The Practice of Biophilic Design*; Yale University Press: New Haven, CT, USA; London, UK, 2018.
21. Wilson, E.O. *Biophilia*; Harvard University Press: Cambridge, MA, USA, 1984.
22. Wilson, E.O. Biophilia and the conservation ethic. In *The Biophilia Hypothesis*; Kellert, S.R., Wilson, E.O., Eds.; Island Press, Shearwater Books: Washington, DC, USA, 1993; pp. 31–32.
23. Ulrich, R.S. Biophilia, biophobia, and natural landscapes. In *The Biophilia Hypothesis*; Kellert, S.R., Wilson, E.O., Eds.; Island Press, Shearwater Books: Washington, DC, USA, 1993; pp. 73–137.
24. Yin, J.; Spengler, J.D. Going biophilic: Living and working in biophilic buildings. In *Urban Health*; Galea, S., Ettman, C.K., Vlahov, D., Eds.; Oxford University Press: New York, NY, USA, 2019.
25. Sanchez, J.A.; Ikaga, T.; Sanchez, S.V. Quantitative improvement in workplace performance through biophilic design: A pilot experiment case study. *Energ. Build.* **2018**, *177*, 316–328. [CrossRef]
26. Gillis, K.; Gatersleben, B. A Review of Psychological Literature on the Health and Wellbeing Benefits of Biophilic Design. *Buildings* **2015**, *5*, 948–963. [CrossRef]
27. Ryan, C.; Browning, W.; Clancy, J.; Andrews, S.; Kallianpurkar, N. Biophilic design patterns: Emerging nature-based parameters for health and well-being in the built environment. *ArchNet-IJAR* **2014**, *8*, 62–76. [CrossRef]
28. Lee, K.T.; Im, J.B.; Park, S.J.; Kim, J.H. Conceptual Framework to Support Personalized Indoor Space Design Decision-Making: A Systematic Literature Review. *Buildings* **2022**, *12*, 716. [CrossRef]

29. Taylor, R.P. The potential of biophilic fractal designs to promote health and performance: A review of experiments and applications. *Sustainability* **2021**, *13*, 823. [CrossRef]
30. Lavdas, A.A.; Schirpke, U. Aesthetic preference is related to organized complexity. *PLoS ONE* **2020**, *15*, e0235257. [CrossRef] [PubMed]
31. Carmody, J.; Sterling, R. *Underground Building Design: Commercial and Institutional Structures*; Van Nostrand Reinhold Co.: New York, NY, USA, 1983.
32. Han, K.T.; Ruan, L.W. Effects of Indoor Plants on Self-reported Perceptions: A Systemic Review. *Sustainability* **2019**, *11*, 4506. [CrossRef]
33. Burchett, M.; Torpy, F.; Tarran, J. Interior plants for sustainable facility ecology and workplace productivity. In *Proceedings of HMAA Conference*; Faculty of Science, Queensland University of Technology: Brisbane, Australia, 2008; Volume 7, pp. 1–12.
34. Park, S.Y.; Song, J.S.; Kim, H.D.; Yamane, K.; Son, K.C. Effects of interior plantscapes on indoor environments and stress level of high school students. *J. Jpn. Soc. Hortic. Sci.* **2008**, *77*, 447–454. [CrossRef]
35. Thomsen, J.D.; Sønderstrup-Andersen, H.K.H.; Müller, R. People–plant relationships in an office workplace: Perceived benefits for the workplace and employees. *HortScience Horts* **2011**, *46*, 744–752. [CrossRef]
36. Pérez-Urrestarazu, L.; Kaltsidi, M.P.; Nektarios, P.A.; Markakis, G.; Loges, V.; Perini, K.; Fernández-Cañero, R. Particularities of having plants at home during the confinement due to the COVID-19 pandemic. *Urban. Urban. Gree* **2021**, *59*, 126919. [CrossRef]
37. Dravigne, A.; Waliczek, T.M.; Lineberger, R.D.; Zajicek, J.M. The Effect of Live Plants and Window Views of Green Spaces on Employee Perceptions of Job Satisfaction. *Hortscience* **2008**, *43*, 183–187. [CrossRef]
38. Qin, J.; Sun, C.; Zhou, X.; Leng, H.; Lian, Z. The effect of indoor plants on human comfort. *Indoor Built Environ.* **2014**, *23*, 709–723. [CrossRef]
39. Dzhambov, A.M.; Lercher, P.; Browning, M.H.; Stoyanov, D.; Petrova, N.; Novakov, S.; Dimitrova, D.D. Does greenery experienced indoors and outdoors provide an escape and support mental health during the COVID-19 quarantine? *Environ. Res.* **2021**, *196*, 110420. [CrossRef]
40. Chen, B.; Qi, X. Protest response and contingent valuation of an urban forest park in Fuzhou City, China. *Urban. Urban. Gree* **2018**, *29*, 68–76. [CrossRef]
41. Lo, A.Y.; Jim, C.Y. Willingness of residents to pay and motives for conservation of urban green spaces in the compact city of Hong Kong. *Urban. Urban. Gree* **2010**, *9*, 113–120. [CrossRef]
42. Majumdar, S.; Deng, J.; Zhang, Y.; Pierskalla, C. Using contingent valuation to estimate the willingness of tourists to pay for urban forests: A study in Savannah, Georgia. *Urban. Urban. Gree* **2011**, *10*, 275–280. [CrossRef]
43. Venkatachalam, L. The contingent valuation method: A review. *Environ. Impact Asses* **2004**, *24*, 89–124. [CrossRef]
44. Latinopoulos, D.; Mallios, Z.; Latinopoulos, P. Valuing the benefits of an urban park project: A contingent valuation study in Thessaloniki, Greece. *Land Use Policy* **2016**, *55*, 130–141. [CrossRef]
45. Spangenberg, J.H.; Settele, J. Value pluralism and economic valuation—Defendable if well done. *Ecosyst. Serv.* **2016**, *18*, 100–109. [CrossRef]
46. Sabyrbekov, R.; Dallimer, M.; Navrud, S. Nature affinity and willingness to pay for urban green spaces in a developing country. *Landsc. Urban. Plan.* **2020**, *194*, 103700. [CrossRef]
47. Raymond, C.M.; Kenter, J.O. Transcendental values and the valuation and management of ecosystem services. *Ecosyst. Serv.* **2016**, *21*, 241–257. [CrossRef]
48. Hoyos, D.; Mariel, P. Contingent valuation: Past, present and future. *Prague Econ. Pap.* **2010**, *4*, 329–343. [CrossRef]
49. Andrade, C.C.; Devlin, A.S. Stress reduction in the hospital room: Applying Ulrich's theory of supportive design. *J. Environ. Psychol. J. Environ. Psychol.* **2015**, *41*, 125–134. [CrossRef]
50. Felsten, G. Where to take a study break on the college campus: An attention restoration theory perspective. *J. Environ. Psychol.* **2009**, *29*, 160–167. [CrossRef]
51. Staats, H.; Kieviet, A.; Hartig, T. Where to recover from attentional fatigue: An expectancy-value analysis of environmental preference. *J. Environ. Psychol.* **2003**, *23*, 147–157.
52. Bateson, J.E.; Hui, M.K. The ecological validity of photographic slides and videotapes in simulating the service setting. *J. Consum. Res.* **1992**, *19*, 271–281. [CrossRef]
53. Stamps, A.E. Simulation effects on environmental preference. *J. Environ. Manag.* **1993**, *38*, 115–132. [CrossRef]
54. Wang, R.; Zhao, J.; Meitner, M.J.; Hu, Y.; Xu, X. Characteristics of urban green spaces in relation to aesthetic preference and stress recovery. *Urban For. Urban Green.* **2019**, *41*, 6–13. [CrossRef]
55. Zhang, Y.; van den Berg, A.E.; van Dijk, T.; Weitkamp, G. Quality over quantity: Contribution of urban green space to neighborhood satisfaction. *Int. J. Environ. Res. Public Health* **2017**, *14*, 535. [CrossRef] [PubMed]
56. Johnston, R.J.; Boyle, K.J.; Adamowicz, W.; Bennett, J.; Brouwer, R.; Cameron, T.A.; Hanemann, W.M.; Hanley, N.; Ryan, M.; Scarpa, R.; et al. Contemporary guidance for stated preference studies. *J. Assoc. Environ. Resour. Econ.* **2017**, *4*, 319–405.
57. Xu, W.; Zhao, J.; Huang, Y.; Hu, B. Design intensities in relation to visual aesthetic preference. *Urban For. Urban Green.* **2018**, *34*, 305–310. [CrossRef]
58. Roth, M. Validating the use of Internet survey techniques in visual landscape assessment—An empirical study from Germany. *Landsc. Urban Plan.* **2006**, *78*, 179–192. [CrossRef]
59. Carson, R.T. Contingent valuation: A user's guide. *Environ. Sci. Technol.* **2000**, *34*, 1413–1418. [CrossRef]

60. Dijkstra, K.; Pieterse, M.E.; Pruyn, A. Stress-reducing effects of indoor plants in the built healthcare environment: The mediating role of perceived attractiveness. *Prev. Med.* **2008**, *47*, 279–283. [CrossRef] [PubMed]
61. McSweeney, J.; Johnson, S.; Sherry, S.; Singleton, J.; Rainham, D. Indoor nature exposure and influence on physiological stress markers. *Int. J. Environ. Health R.* **2021**, *31*, 636–650. [CrossRef] [PubMed]
62. Tonia, G.; Carol, B. Are biophilic-designed site office buildings linked to health benefits and high performing occupants? *Int. J. Environ. Res. Public Health* **2014**, *11*, 12204–12222.
63. Nejati, A.; Rodiek, S.; Shepley, M. Using visual simulation to evaluate restorative qualities of access to nature in hospital staff break areas. *Landsc. Urban Plan.* **2016**, *148*, 132–138. [CrossRef]
64. Yin, J.; Arfaei, N.; MacNaughton, P.; Catalano, P.J.; Allen, J.G.; Spengler, J.D. Effects of biophilic interventions in office on stress reaction and cognitive function: A randomized crossover study in virtual reality. *Indoor Air* **2019**, *29*, 1028–1039. [PubMed]
65. Suppakittpaisarn, P.; Jiang, B.; Slavenas, M.; Sullivan, W.C. Does Density of Green Infrastructure Predict Preference? *Urban For. Urban Green.* **2019**, *40*, 236–244. [CrossRef]
66. Jiang, B.; Chang, C.Y.S.; Ullivan, W.C. A dose of nature: Tree cover, stress reduction, and gender differences. *Landsc. Urban. Plan.* **2014**, *132*, 26–36. [CrossRef]
67. Chiang, Y.; Li, D.; Jane, H. Wild or tended nature? The effects of landscape location and vegetation density on physiological and psychological responses. *Landsc. Urban Plan.* **2017**, *167*, 72–83. [CrossRef]
68. Bao, R. Excessive design of city landscape environment (in Chinese). *Anhui Archit.* **2006**, *13*, 24–25.
69. Kim, U.; Wineman, J. *Are Windows and Views Really Better? A Quantitative Analysis of the Economic and Psychological Value of Windows*; Working Paper; Taubman College of Architecture and Urban Planning, University of Michigan: Ann Arbor, MI, USA, 2005.
70. Huang, T.L. Restorative experiences and online tourists' willingness to pay a price premium in an augmented reality environment. *J. Retail. Consum. Serv.* **2021**, *58*, 102256. [CrossRef]
71. Barbiero, G.; Berto, R. From biophilia to naturalist intelligence passing through perceived restorativeness and connection to nature. *Ann. Rev. Res.* **2018**, *3*, 555604.
72. Hartig, T.; Kaiser, F.G.; Bowler, P.A. Psychological restoration in nature as a positive motivation for ecological behavior. *Environ. Behav.* **2001**, *33*, 590–607. [CrossRef]
73. Marselle, M.R.; Irvine, K.N.; Lorenzo-Arribas, A.; Warberdf, S.L. Does perceived restorativeness mediate the effects of perceived biodiversity and perceived naturalness on emotional well-being following group walks in nature? *J. Environ. Psychol.* **2016**, *46*, 217–232. [CrossRef]
74. O' Donnell, M.; Evers, E.R.K. Preference Reversals in Willingness to Pay and Choice. *J. Consum. Res.* **2019**, *45*, 1315–1330. [CrossRef]
75. Jorgensen, B.S.; Wilson, M.A.; Heberlein, T.A. Fairness in the contingent valuation of environmental public goods: Attitude toward paying for environmental improvements at two levels of scope. *Ecol. Econ.* **2001**, *36*, 133–148.
76. Kotchen, M.J.; Reiling, S.D. Environmental attitudes, motivations, and contingent valuation of nonuse values: A case study involving endangered species. *Ecol. Econ.* **2000**, *32*, 93–107. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# Spatial Distribution and Accessibility Evaluation of National Water Parks in China

**Chenming Zhang [1,*], Bei He [2], Wei Li [3,*] and Chunyang Guo [4]**

[1] College of Architecture, North China University of Water Resources and Electric Power, Zhengzhou 450046, China
[2] School of Construction Management and Real Estate, Henan University of Economics and Law, Zhengzhou 450046, China
[3] School of Art and Design, Zhengzhou University of Aeronautics, Zhengzhou 450046, China
[4] School of Tourism Management, Henan Finance University, Zhengzhou 451464, China
* Correspondence: zhangchenming@ncwu.edu.cn (C.Z.); lw1990@zua.edu.cn (W.L.)

**Abstract:** A water park is a nature-based site along a river or water management project that plays a vital role in protecting the local ecological system and providing water recreation, making it an essential component of China's ecological and ecotourism security strategy. This study sought to portray the distribution of China's 878 National Water Parks (NWPs) and to visualize the pattern of accessibility for NWP resources by the gravity-2SFCA method. The investigation produced the following findings: (1) The national-scale pattern of ecotourism and water recreation can be revealed by the distribution of NWPs, which were concentrated on the eastern side of the "Hu Line" but were dispersed on the western side. (2) NWPs can function as detectors of various endowment and management modes of basin-scaled water resources through the relationship between different categories of NWPs and their locations, which can provide guidance for regional planners. (3) The accessibility of NWPs is an effective indicator for revealing spatial disparity between the supply of NWP resources and the population distribution. Then, the general NWP development strategy can be made based on a hot-spot visualization analysis of accessibility patterns.

**Keywords:** national water park; spatial pattern; accessibility; exploratory spatial data analysis

**Citation:** Zhang, C.; He, B.; Li, W.; Guo, C. Spatial Distribution and Accessibility Evaluation of National Water Parks in China. *Sustainability* **2023**, *15*, 11621. https://doi.org/10.3390/su151511621

Academic Editor: Hossein Bonakdari

Received: 10 May 2023
Revised: 21 July 2023
Accepted: 25 July 2023
Published: 27 July 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Globally severe hydrological extremes, such as floods and droughts, occur frequently across the globe [1,2]. Water management projects, such as dams, reservoirs, and irrigation canals, are essential for flood control, drought relief, hydropower generation, water resource protection, and soil conservation [3,4].

Wang et al. [3] and Xu et al. [4] found that attaining the high standards required for efficient water management is particularly difficult for single-purpose water conservation projects, prompting the development of multi-purpose projects. In addition to the conventional functions, nature conservation and sightseeing become essential components in the development of multipurpose projects, demonstrating a significant potential for boosting local economies [5]. Therefore, many water conservation projects, such as the Aswan Dam in Egypt, the Three Gorges Dam in China, and the Tennessee Valley Authority in the United States, have been adapted for ecotourism and recreation [6,7].

From the perspective of ecosystem services [8], the aforementioned water facilities provide a variety of ecological and socioeconomic attributes that fall under three categories of services (provisioning services, regulation and maintenance services, and cultural services) [8,9]. The provisioning services primarily include "hydropower supplying" and "water for stock" (drinking and non-drinking water), which generate substantial and direct economic benefits. The regulation and maintenance services consist primarily of the "maintaining populations and habitats" service, the "flood protection" service, and the "erosion

prevention" service [8,9], the value of which rise as water management is improved. Four sub-services comprise the cultural services: amenity, recreation, education and research, and spiritual and aesthetic. The subservices of water amenity are the overall quality, experience, and natural values provided by the existence of a lake [10]. The sub-services of water recreation make possible water-based activities such as leisure boating, sightseeing, swimming, recreational angling, and sport fishing [11,12]. The water education and research sub-services enable the general public to comprehend the science and engineering of water [13]. The spiritual and artistic sub-services consist of aesthetic values, a sense of place, cultural heritage values, and other immaterial attributes [14]. In addition, ecotourism, a result of such water facilities, has been found to be advantageous for poverty alleviation, job creation, and market promotion [15], thereby promoting the sustainable development of the local economy and society.

The National Water Parks (NWP) system is China's strategy for enhancing the ecological and socioeconomic attributes of man-made water facilities. China has constructed a large number of water conservation facilities, accounting for nearly half of the world's dams, 20 percent of global hydropower generation, and 21 percent of the world's irrigated area to address the problems of severe water scarcity and extensive flood threats [16]. Many of them feature breathtaking landscapes, attractive surroundings, and cultural and historical sites, which provide a huge space for the development of NWPs.

Moreover, the NWP system follows top-down management from the Ministry of Water Resources to local government. In the public documents of the Ministry of Water Resources, NWP can be defined as a scenic location constructed around a water body or water management project with sufficient environmental capacity and landscape resources to meet the needs of ecological protection, ecotourism, recreation, cultural promotion, and educational activities [17,18]. Typically, NWP integrates diverse landscapes related to hydrology, geography, astronomy, biology, engineering, and humans, thereby performing six primary functions, including maintaining water engineering projects, protecting water resources, enhancing the water environment, restoring water ecology, promoting water culture, and developing water economy.

From an academic perspective, the NWP system in China is very similar to the Protected River System (PRS) or National Wild and Scenic River System (NWSRS) in the United States [19]. These systems play a significant role in the efficacy and effectiveness of ecosystem and biodiversity conservation, attracting interdisciplinary research interest [20–22]. The distribution pattern of NWPs is typically a function of ecoregions, which are influenced by the interaction of natural and human factors such as hydrologic conditions, unique ecosystems, water administrative management policy, and urbanization level [23–25]. From the perspectives of ecology and water-related professions, ecological footprint, ecosystem services, and their evolutionary processes are essential to waterfront management, which can direct ecology restoration and ecological flow allocation [26–31]. According to tourism studies, the greatest concern is how to accomplish sustainable development in the case of NWPs, given the increase in the number of tourists and the overloading of environmental carrying capacity [32–34]. The specific issues are water tourism development, aquatic heritage protection, tourist behavior, and the perception of scenic imagery [35–38]. In addition, intersectional studies between NWPs and other land-protected scenic areas have become a trending topic [39,40]. Unlike other land-based protected scenic areas, NWPs make extensive use of rivers, shorelines, and water management facilities, where artificial projects are permitted to ensure effective flood control and drought resistance. Therefore, NWPs require a unique range of management techniques and are more closely linked to economic and social activities than other types of natural reserves [41,42].

The following is a summary of the limitations of previous research.

(1) The multi-scaled portrait of water facilities for ecotourism and recreation has not been illustrated. There are various research values at various scales. The watershed scale is suitable for comprehending the relationship between water park categories and locations [43]. The national dimension is more suitable for revealing the spatial

disparities between water parks, traffic networks, populations, and cities. However, multi-scale investigations have received considerably less attention.

(2) The water facilities for ecotourism and recreation have not been considered simultaneously as "sources" and "sinks". The majority of previous studies [44,45] regarded water-based scenic locations as tourist destinations, i.e., a "sink" that attracts visitors. Few studies have examined the dialectical relationship between "sources" and "sinks" in both directions, and scenic areas have been identified as water resource "sources".

(3) The interaction between various locations of supply (water ecotourism and recreation resources) and population demands has not yet been investigated. Regional studies have traditionally calculated the per capita value of resources using the so-called "container approach". For this method, the study area is divided into distinct spatial "containers" with specific boundaries, and the per capita resources accessed in each container are estimated without taking visitor movement across the boundary [46] into account. In actuality, people are not restricted to visiting the water park closest to them, and each water park may receive visitors from various neighborhoods. The many-to-many relationship necessitates a more thorough analysis of spatial accessibility.

(4) The current accessibility evaluation for water parks is insufficient to support the coordinated sustainable development of WNPs with traffic, population, and cities. On the one hand, case studies for accessibility have not included the visualization and agglomerative patterns of hotspots as a further analysis pertinent to NWPs planning. On the other hand, there is a lack of comparative studies and general regulations for various regions or nations that incorporate accessibility into the ecological and socioeconomic values of water parks.

Consequently, the study seeks to overcome the aforementioned limitations and accomplish the innovative objectives: (1) Depict the spatial pattern of water ecotourism and recreation in China by combining ecological and geographic perspectives at both the national and basin scales. (2) Evaluate the prospective NWPs resources accessed per capita, taking trans-regional activities into account, so that NWP facilities serve not only the cities in which they are zoned, but also neighboring cities. In addition, the accessibility algorithm incorporates the gravity function to simulate the distance attenuation effect. (3) Visualize the accessibility of NWPs resources using a comprehensive national database, and quantitatively disclose the hot-spot and cold-spot patterns of accessibility values using an additional ESDA (Exploring Spatial Data Analysis) method, which will have more application for NWP strategies. (4) Derive general conclusions from Chinese experience to regulate the layout and development of NWPs that are compatible with sustainability principles such as comprehensive resource utilization and enhancement of resource utilization capacity for traditional practices [47].

The remainder of the paper is structured as shown in Figure 1: first, a database of NWPs, population, traffic networks, and cities is compiled. At various dimensions, the spatial patterns of NWPs are portrayed. In the subsequent segment, the accessibility of NWPs and its spatial agglomeration pattern are evaluated and depicted. The report concludes with a discussion and generalizations of the results applicable to NWP strategies.

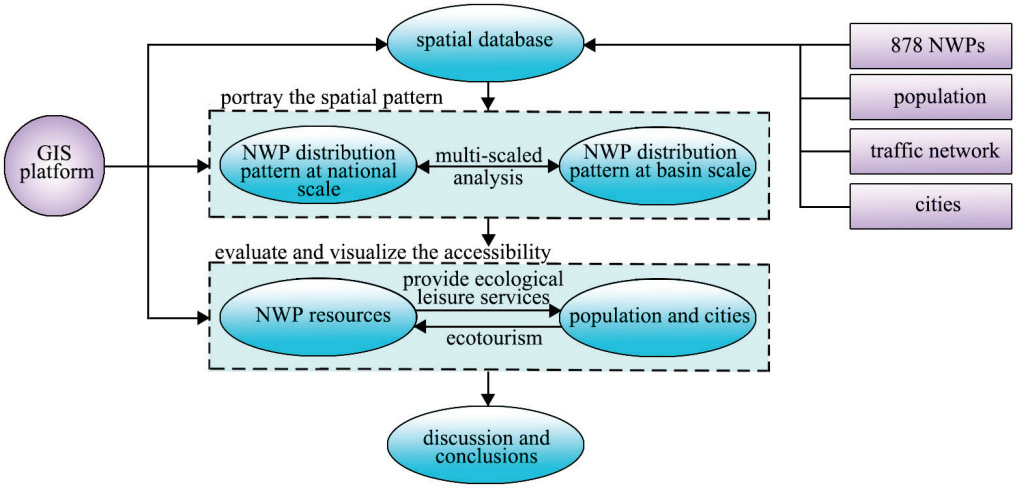



**Figure 1.** Flow chart of the whole research.

## 2. Data Process and Research Methods

### *2.1. Data Process*

This study includes 878 NWPs, which can be categorized into six groups, namely, 391 reservoir type (RES), 39 wetland type (WLD), 193 natural river and lake type (NRL), 194 urban river and lake type (URL), 24 irrigation area type (IRA), and 37 water and soil conservation area type (WSC) [48]. The locations of the 878 NWPs, as provided by China's Ministry of Water Resources, are depicted in Figure 2. LandScan (https://landscan.ornl.gov/, (accessed on 20 December 2022)) provides the population amount in the year 2021 (Figure 3a). Baidu Maps is used to gather the transportation network (Figure 3b). It is designated that the speed on the highway is 100 km/h, that of national roads is 80 km/h, and that of provincial roads is 60 km/h based on the difference in travelling speeds between road types [49].

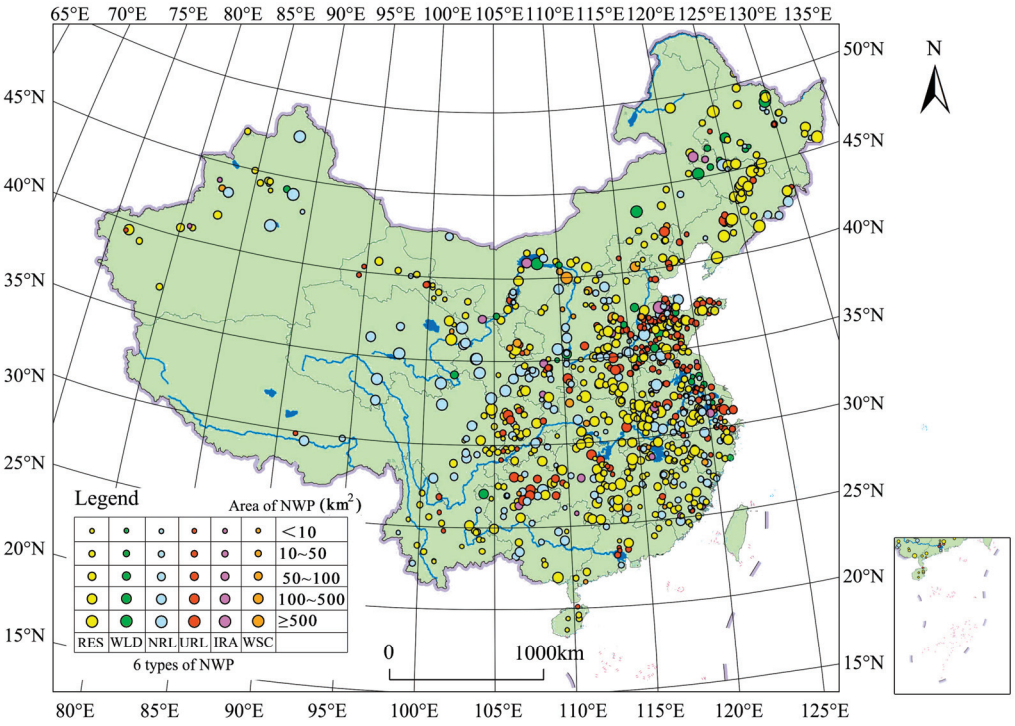
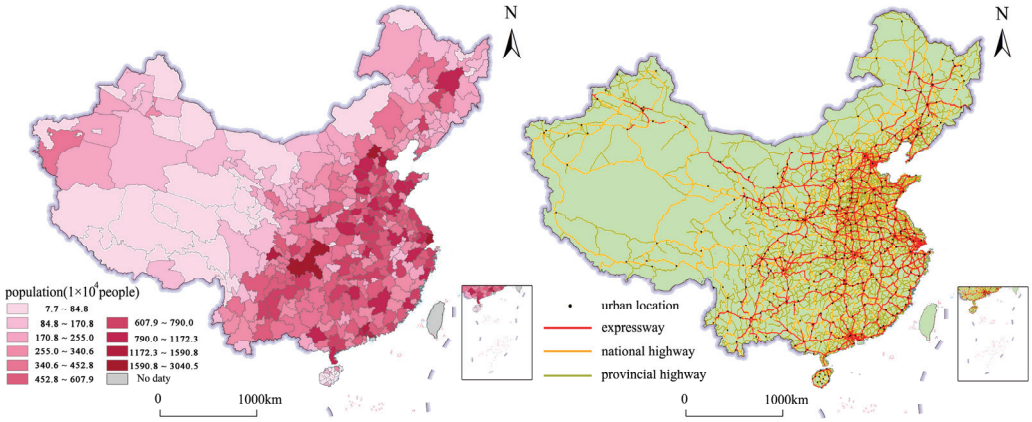



**Figure 2.** The types, scale, and distribution of 878 NWPs.




(a) population distribution (b) highway network

**Figure 3.** The visualization of the basic data (**a**) is the distribution of population in 2021, (**b**) is the highway network in China.

### *2.2. Research Methods*

To analyze the spatial distribution pattern and accessibility of NWPs, the standard deviation ellipse, kernel density, enhanced two-step floating catchment area (2SFCA), and exploratory spatial data analysis (ESDA) are presented. In data processing, ArcGIS, Jupyter notebook, and Geoda are utilized.

#### 2.2.1. Kernel Density

Kernel density estimation (KDE) is used to draw the data map of the density distribution of dots (The dots in this research are NWPs). It is crucial for spatial analysis to visualize where the density is high and where the density is low if the dots are distributed unevenly. The basic idea of the KDE is that the spatial information of the dots input is spread on a plane, outputting a raster image with kernel density of each pixel value measured. The kernel density of pixel $x$ can be calculated from the dots within a certain range around pixel $x$ using the formula described as follows [50]:

$$f(x) = \frac{1}{nh^2}\sum_{i=1}^{n} k\left(\frac{d(x,i)}{h}\right) \quad (1)$$

$f(x)$ is the kernel density of pixel $x$, $h$ is the bandwidth (fixed radius), which influences the smoothness of the kernel density distribution, $n$ is the number of NWP points within the bandwidth range, $d(x,i)$ is the distance between the center point of the pixel $x$ and the NWP point $i$ within the bandwidth, and $k$ is the kernel function, which determines the density-reduction process as the distance from the NWP points increases. The KDE can be understood to be the result of spatial probability accumulation resulting from summation [51].

#### 2.2.2. Standard Deviation Ellipse

The standard deviation (SD) ellipse method is a common way to reveal the overall directional characteristic and the extension pattern of dots. A particular SD ellipse can be drawn by a set of sample dots. The center of the SD ellipse is determined by the average location of the dots; the long axis direction of the SD ellipse orients the main distribution trends of the dots; the lengths of the long axis and short axis of the SD ellipse represent the maximum and minimum extension of the dots in corresponding directions, respectively. The SD ellipse is more oblate the more significant directionality the sample dots present. Basic parameters of the SD ellipse include the center coordinate, standard deviations of the $x$- and $y$-axes, and rotation angle. The formula for calculation is as follows [52]:

$$x^*{}_i = x_i - \overline{X}; \quad y^*{}_i = y_i - \overline{Y} \quad (2)$$

$$\tan\theta = \frac{(\sum_{i=1}^{n} w_i^2 {x^*}_i^2 - \sum_{i=1}^{n} w_i^2 {y^*}_i^2) + \sqrt{(\sum_{i=1}^{n} w_i^2 {x^*}_i^2 - \sum_{i=1}^{n} w_i^2 {y^*}_i^2)^2 + 4(\sum_{i=1}^{n} w_i^2 {x^*}_i^2 {y^*}_i^2)^2}}{2\sum_{i=1}^{n} w_i^2 {x^*}_i y^*_i} \quad (3)$$

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n} (w_i {x^*}_i \cos\theta - w_i {y^*}_i \sin\theta)^2}{\sum_{i=1}^{n} {w_i}^2}} \; ; \; \sigma_y = \sqrt{\frac{\sum_{i=1}^{n} (w_i {x^*}_i \sin\theta - w_i {y^*}_i \cos\theta)^2}{\sum_{i=1}^{n} {w_i}^2}} \quad (4)$$

In the formula, $(\overline{X}, \overline{Y})$ is the coordinate of gravity point of NWPs in the river basin and $(x_i, y_i)$, $(x^*_i, y^*_i)$ are the absolute coordinates and relative coordinates of the $i$th NWP, respectively. $\theta$ is the angle of rotation of the ellipse (due north is 0 degrees, clockwise rotation). $w_i$ is the weight by the areas, and $\sigma_x$ and $\sigma_y$ are the standard deviations along the $x$ axis and $y$ axis, respectively.

2.2.3. Distance-Decay Improved Two-Step Floating Catchment Area

The two-step floating catchment area (2SFCA) is a GIS method to evaluate the accessibility indicator which measures how many resources can be obtained per capita in a certain area. The model basically assumes the following: (1) That there exists some points supplying resources and some areas need to be supplied; (2) each point allocates its resources to the areas around it within a certain distance (searching threshold), and the quantity of allocation is depend on both the population size and the distance; (3) each area can obtain resources from the points within the searching threshold; and (4) the total supply of resources from the same resource point is limited to its capacity. Then, the accessibility of the resource for each area can be computed by two steps of searching as follows [53–55]:

Scanning for city centers surrounding NWPs. Count the number of city sites within each NWP's criterion and compute the supply-to-population ratio at each spatial unit.

$$R_j = \frac{S_j}{\sum_{\{d_{ij} \le d_0\}} w(d_{ij}) D_i} \quad (5)$$

In the formula above, $R_j$ is the ratio of supply to population at the supply point $j$, $S_j$ is supply scale at the supply point $j$ represented by NWP area, $D_i$ is the total population of city $i$, $d_0$ is the searching threshold, and $d_{ij}$ is the time cost from city point $i$ to supply point $j$.

Searching NWPs around city points as centers. Spatial accumulation of $R_j$ at point $j$ is computed.

$$A_i = \sum_{\{d_{ij} \le d_0\}} w(d_{ij}) R_j \quad (6)$$

where $A_i$ is the accessibility of NWP resources at city $i$. Obviously, the essence of $A_i$ is the opportunity for accumulation of "supply/population ratio" at location $i$, which refers to the relative ease by which a given NWP can be reached from a given location. The higher $A_i$ is, the more accessible location $i$ is, and vice versa.

A distance-decay function $w$ $(x)$ is introduced into the original form of 2SFCA and can be written as Formula (7), aiming to simulate the distance attenuation effect from the supplying points (NWPs) to the cities.

$$w(d_{ij}) = \begin{cases} 0 & d_{ij} > d_0 \\ \frac{1}{{d_{ij}}^2} & d_{ij} \le d_0 \end{cases} \quad (7)$$

This gravity function benefits from the advantages of concision and accuracy, and proved to be more accordant with practice. In addition, the downtown location rather than the centroid of the administrative district is selected as the city center.

2.2.4. Exploratory Spatial Data Analysis (ESDA)

The first law of geography states that "everything is related to everything else, but near things are more related to each other" [56]. The ESDA method reveals to what degree the near things are related to each other. More academically, the ESDA is typically employed for measuring and mapping the properties or spatial patterns of geography objects, identifying the spatial clustering of social and economic phenomenon, and detecting the spatial differences and correlation degree of the research area. The foundation of ESDA is the spatial autocorrelation analysis based on a combination of graphic and statistical data, which consists of two methods: global spatial autocorrelation analysis and local spatial autocorrelation analysis [57].

(1) Global Spatial Autocorrelation

Global spatial autocorrelation describes the spatial features throughout the study area. Moran's $I$ index is a measurement index of global spatial autocorrelation, which can be calculated as follows:

$$\begin{aligned} &\text{Moran's } I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i-\overline{x})(x_j-\overline{x})}{(\sum_{j=1}^{n}\sum_{j=1}^{n} w_{ij})\sum_{i=1}^{n}(x_i-\overline{x})^2} \\ &w_{ij} = \begin{cases} 1 & \textit{when the region } i \textit{ and the region } j \textit{ are connected} \\ 0 & \textit{when the region } i \textit{ and the region } j \textit{ are not connected} \end{cases} \end{aligned} \tag{8}$$

$x_i$ and $x_j$ are the values of accessibility calculated by Formula (6) at region $i$ and region $j$, respectively. $x$ is the average of $x_i$. $w_{ij}$ is the spatial weights matrix. The value of Moran's $I$ is within the scope of $[-1, 1]$. When Moran's $I > 0$, it represents positive spatial correlation. When Moran's $I < 0$, negative spatial correlation is represented. When Moran's $I = 0$, a lack of correlation is represented.

(2) Local Spatial Autocorrelation

The global Moran's $I$ reveals only the overall spatial dependence of geographical phenomena and is incapable of comparing local spatial differences. Consequently, a local spatial autocorrelation analysis is required [58]. Local indicators of spatial association (LISA) are utilized to indicate the dissimilarity between a particular location and its environs. The $i$th region's LISA index is computed as follows:

$$I_i = \frac{x_i - \overline{x}}{S^2}\sum_{j}^{n} w_{ij}(x_j - \overline{x}) \tag{9}$$

$x_i$, $x_j$, $x$, and $w_{ij}$ are the same parameters mentioned above for the global spatial autocorrelation. $S^2$ is the discrete variance of $x_i$. At a given significance level, a LISA aggregation map is created, combining the LISA significance level with the scatter plot, in which the "hot spot" and the "cold spot" can be identified. The LISA figure can be divided into four significant types: ① High–high aggregation type: $I_{LISA} > 0$, the accessibility level of area $i$ and its adjacent areas are both higher than the average level; ② Low–low agglomeration type: $I_{LISA} > 0$, the accessibility level of area $i$ and its adjacent areas are both lower than the average level; ③ High–low aggregation type: $I_{LISA} < 0$, the accessibility level of area $i$ is higher than the average level while its adjacent areas are lower than the average; ④ Low–high aggregation type: $I_{LISA} < 0$, the accessibility level of area $i$ is lower than the average level while its adjacent areas are higher than the average.

## 3. Patterns of Spatial Distribution of NWPs

### *3.1. Distribution Pattern of National-Scale NWPs*

Figure 4 depicts the global distribution of each NWP type, revealing a typical pattern of clustering in the eastern region of the Hu Huanyong Line and scattering in the western region.

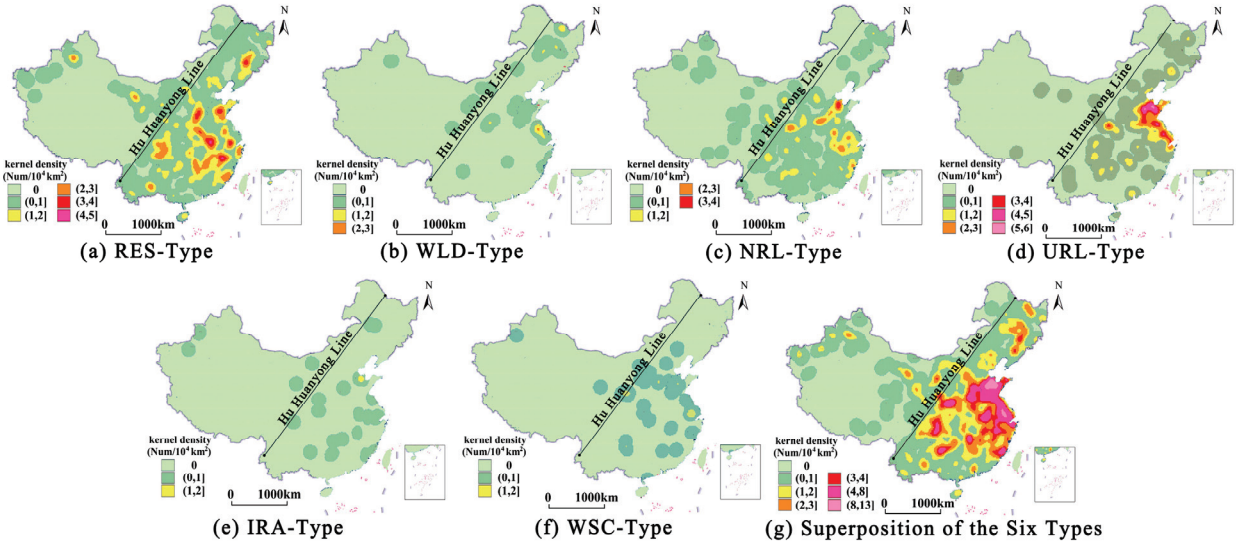



**Figure 4.** The kernel distribution of each type of NWP.

The kernel density of a particular type of scenic location ranged from 0 to $6/10^4$ km$^2$, whereas the kernel density of each type after superposition ranged from 0 to $13/10^4$ km$^2$ (Figure 4). Low-density areas (0~1 Num/$10^4$ km$^2$), medium-density areas (1~2 Num/$10^4$ km$^2$), medium-to-high-density areas (2~3 Num/$10^4$ km$^2$), and high-density areas (>3 Num/$10^4$ km$^2$) were categorized to disclose the distribution pattern of NWP hotspots. There were 391 RES-Type NWPs with a maximum kernel density of $4.25/10^4$ km$^2$ (see Figure 4a). Medium-high-density and high-density areas were dispersed, predominantly along the eastern coast, in six central provinces, and in portions of eastern Sichuan. There were 194 URL-Type NWPs (see Figure 4d), and the maximum kernel density was $5.52/10^4$ km$^2$, with medium-high-density areas and high-density areas concentrated in Shandong province and extending into patches from Jiangsu province to the Yangtze River Delta; high-density areas also exist in a single point in Xi'an. Figure 4c depicts 193 NRL-Type NWPs with a maximal kernel density of $3.67/10^4$ km$^2$. Near Binzhou in Shandong province, a solitary high-density zone was identified, while the medium-high-density regions were sporadically distributed and relatively small. The IRA-Type (see Figure 4e) has 24 NWP spots, whereas the WLD-Type (see Figure 4b) and WSC-Type (see Figure 4f) have 39 and 37 NWP spots, respectively. Generally, the kernel density of these scenic areas is below $1/10^4$ km$^2$, signifying a small number. There were few areas of medium-high- and high-density aggregation, and low-density areas were dispersed across the landscape, with more in the east and fewer in the west.

Based on the superposition of the six types on the integrated map (Figure 4g), the kernel density was higher in the east and lower in the west. Multiple aspects of the ecological and human environment determined the distribution of NWPs. The emergence of medium-high- or high-density areas necessitated the following conditions: the areas must be surrounded by sufficient water resources, partially exploited through water conservation projects, and have sufficient water to fulfil local industrial, agricultural, or urban needs. In addition, the scenic clusters may be surrounded by a dense population, communities, a transit system, and an abundance of water conservancy heritages (such as the area surrounding the Beijing–Hangzhou Grand Canal). If the aforementioned conditions are met, the water value chain can be enhanced because water resources can be converted into water landscape resources. The strong similarity between the macroscopic distribution

of NWPs and the Hu Huangyong Line reveals the spatial–temporal connections between natural geographical elements and human geographic components in China.

### *3.2. Pattern of NWP Distribution at the Basin Scale*

Using watersheds as the analyzing unit, the relationships between NWPs and the main rivers and streams were revealed based on the waters and shorelines. To illustrate the distribution and expansion direction of NWPs at the watershed scale, standard deviation ellipses for NWPs were generated for each of the nine watersheds (Figure 5) and the ratio of long to short semiaxes of each ellipse is shown in Table 1. The Yangtze River, Yellow River, and Huai River basins accounted for 63.4% of the total number of NWPs, totaling 557 (Figure 5 and Table 1). These are the overarching characteristics: (1) The direction of each standard deviation's long axis is considered. In accordance with river trends on a watershed scale, ellipses are present. (2) The ratio of the long axis to the short axis ranges from 1 to 3, with a mean of 1.99. Thus, a strip distribution characteristic exists at the scale of a basin; the longitudinal dispersion degree is roughly double that of the width. (3) According to the degree of strip extension, WLD type > URL type > NRL type > WSC type > IRA type > RES type. The difference in deviation of ellipse shape between different NWP types can be explained as follows: WLD-Type NWPs were more prevalent in the intermediate and lower river reaches. They differed considerably from other types in terms of their standard deviation ellipse, and a few of these NWPs were slightly inconsistent with the watershed's overall direction. URL-Type NWPs were located in the central cities of the watershed, and these cities constituted the axis of economic development for the watershed, causing the standard deviation ellipse to be long and skinny. The NRL-Type NWPs were typically situated on either side of the major rivers, and their standard deviation ellipse closely resembled the watershed's overall shape. WSC and IRA-Type NWPs were uncommon, and no discernible geographic pattern was observed. RES-Type NWPs were frequently built on small- to medium-sized reservoirs, which were common and widely distributed in tributaries. In contrast, only a few of the large reservoirs located in the principal streams have been developed as NWPs, as their primary purpose was water engineering rather than landscape. Consequently, RES-Type standard deviation ellipses were relatively round compared to those of other varieties.

**Table 1.** Ratio of long- to short-half axis of each standard deviational ellipse.

| | RES-Type | WLD-Type | NRL-Type | URL-Type | IRA-Type | WSC-Type | Superposition of the Six Types |
|---|---|---|---|---|---|---|---|
| Yangtze River Basin | 1.85 (151) | 12.02 (4) | 1.99 (66) | 2.84 (51) | 2.23 (7) | 1.91 (13) | 1.99 (292) |
| Yellow River Basin | 1.59 (39) | 1.48 (9) | 3.16 (43) | 2.22 (17) | 1.99 (5) | 2.56 (10) | 2.02 (123) |
| Huai River Basin | 2.59 (43) | 1.86 (8) | 2.13 (16) | 1.60 (68) | / (2) | 1.61 (5) | 1.93 (142) |
| Hai River Basin | 2.93 (26) | 2.23 (3) | 3.07 (8) | 1.87 (23) | / (2) | 2.62 (4) | 1.71 (66) |
| Pearl River Basin | 1.93 (26) | / (0) | 2.86 (12) | 9.23 (5) | / (2) | / (2) | 1.98 (47) |
| Songliao River Basin | 1.40 (45) | 3.30 (11) | 1.13 (12) | 2.37 (14) | / (2) | / (1) | 1.46 (85) |
| Continental River Basin | 3.23 (24) | / (2) | 2.02 (9) | 39.28 (4) | / (2) | / (1) | 2.53 (42) |
| Southeastern Rivers Basin | 2.63 (30) | / (2) | 2.48 (22) | 2.09 (10) | / (2) | / (1) | 2.56 (67) |
| Southwestern Rivers Basin | 1.62 (7) | / (0) | 1.90 (5) | / (2) | / (0) | / (0) | 2.69 (14) |
| Weighted average | 2.07 | 3.41 | 2.36 | 3.08 | 2.13 | 2.15 | 1.99 |

Note that the value in parentheses is the number of NWPs in each watershed, while the symbol "/" indicates that the NWP points in the watershed were too few to form a standard deviation ellipse and did not contribute to the computation of the mean.

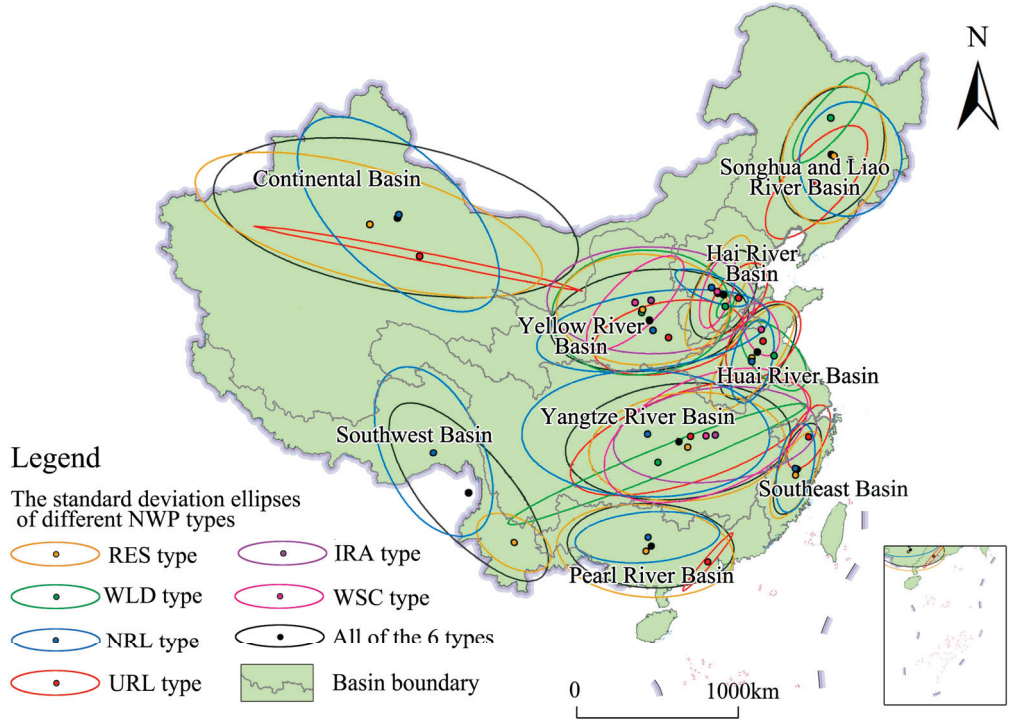
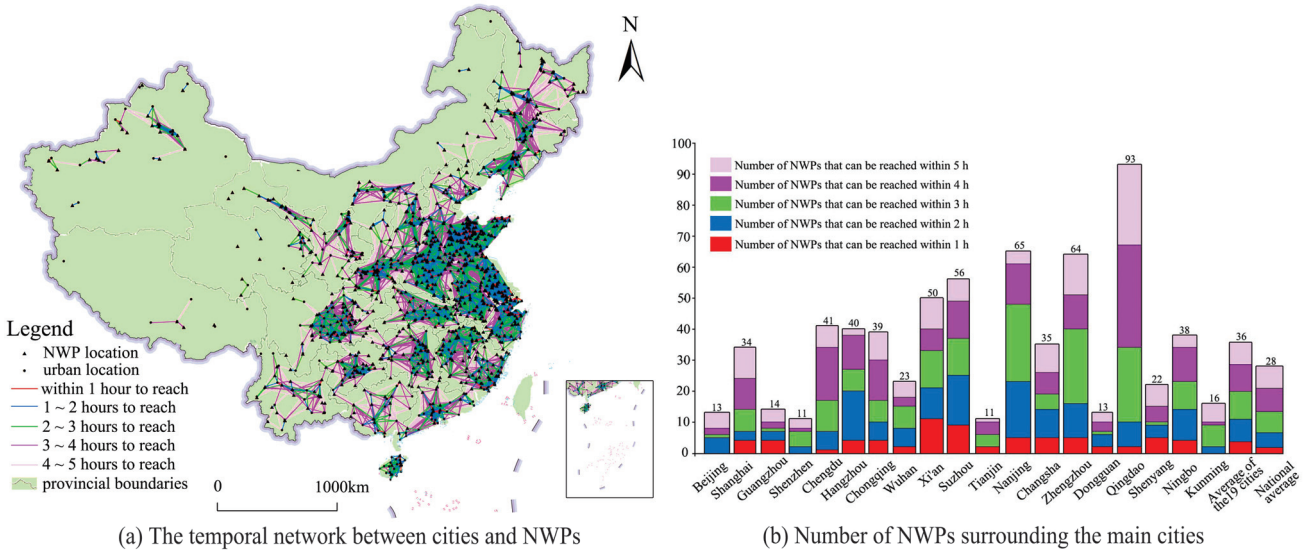



**Figure 5.** Standard deviational ellipses of NWPs in each basin.

## 4. Accessibility of NWPs Resources Based on Transportation, Population, and Cities

### *4.1. Road Network Connecting NWPs and Urban Centres*

The study area was divided into 362 spatial districts based on administrative divisions at the national level. The GIS platform was utilized to determine the central location of the major city in each prefecture district. Figure 6a depicts the subsequent establishment of a spatiotemporal connection network between the cities and their accessible NWPs within 5 h. Using each city as a starting point, the quantity of NWPs within the various radiation radii was tallied. Figure 6b exhibits only the number of NWPs that are accessible from the 21 largest cities (first-tier or new first-tier cities) to conserve space.




(a) The temporal network between cities and NWPs

(b) Number of NWPs surrounding the main cities

**Figure 6.** The temporal network and data statistics between cities and NWPs.

The starting and ending sites of each connecting line in the network depicted in Figure 6a were cities and NWPs. The network was primarily concentrated in eastern and central China. Local networks were dense at the provincial level in Shandong, Henan, Anhui, Jiangsu, and Zhejiang, where interprovincial connectivity was robust. In these regions, it was advantageous to have a NWP representative travel across provinces. Due to insufficient road network development in these regions, the local network was sparse in Xinjiang, Tibet, and Qinghai provinces, with some isolated points. Other provinces exhibited the following pattern of group development: a relatively independent sub-network formed within the province, whereas interprovincial connections were quite loose, with spaces consistent with the direction of the administrative boundary.

As demonstrated in Figure 6b: (1) As the radius of radiation expanded, the number of NWPs that radiated grew, with first-tier and new first-tier cities serving as the center. The rate of development was greatest in Qingdao and lowest in Tianjin. (2) There was a statistically significant difference in the number of NWPs that were accessible from the major cities enumerated in Figure 6b. Xi'an had the greatest number of NWPs reachable within a 1 h circle ($n$ = 11), whereas Beijing, Shenzhen, and Kunming had the fewest ($n$ = 0). Qingdao had the most NWPs accessible within a 5 h circle ($n$ = 93), which was 8.5 times greater than Tianjin or Shenzhen, which had the fewest ($n$ = 11). Beijing, Shenzhen, Tianjin, Dongguan, and Kunming had fewer NWPs than the national average, whereas the majority of significant cities had more. In the aforementioned cities, NWPs were not the predominant type of multipurpose water conservation initiatives.

### *4.2. Mapping the Accessibility of NWPs and Measuring Its Spatial Autocorrelation*

The accessibility of NWP resources for each spatial unit was computed and mapped (see Figure 7a,d) based on the spatial–temporal relationship between NWPs and localities depicted in Figure 6. In addition, exploratory spatial data analysis (ESDA) was performed to identify the accessibility value peaks in Figure 7b,e.

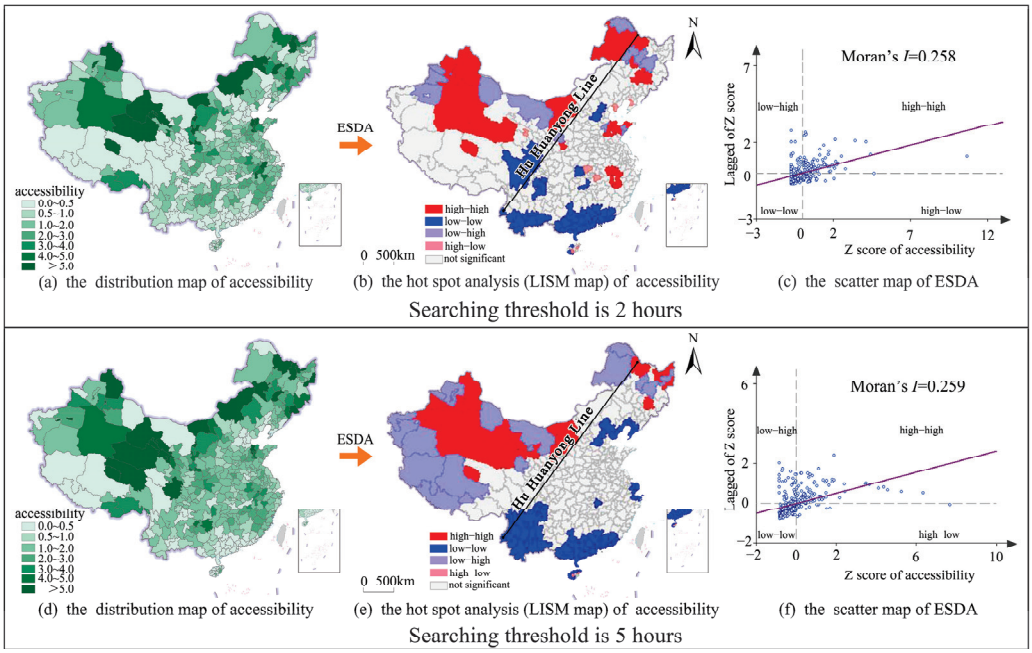



**Figure 7.** Accessibility of NWPs computed by different service radial thresholds ((**top**): 2 h; (**bottom**): 5 h).

Overall, the accessibility value distribution exhibited a macro pattern of being high in the north and low in the south, which did not correspond to the kernel density distribution of NWPs. The justification will be discussed in the discussion section. With 2 h and 5 h thresholds, the utmost value of accessibility is calculated to be 24.23 and 19.61, respectively.

According to the ESDA results, the values of global Moran's *I* were 0.258 and 0.259 when the search thresholds were 2 h and 5 h, respectively; both values passed the significance test, indicating that the accessibilities for NWP resources calculated in different trip radii share similar global spatial agglomeration characteristics. Local spatial autocorrelation displays similar characteristics. The districts with high–high clustering in both scenarios were predominantly located in the northwest (Urumqi, Altay, and Korla in Xinjiang, Haixi in Qinghai, and Bayannur and Erdos in Inner Mongolia). In contrast, Beijing, Tianjin, Hebei, Guangdong, and Yunnan made up the majority of the regions with low–low concentration in both scenarios.

There were differences between Figure 7b,e, indicating that the accessibility pattern was sensitive to variations in thresholds for searching. A comparison is made between the hot spot maps visualized by 2 h searching threshold and 5 h searching threshold values.

(1) In the map of 2 h, both the hot spot areas (high–high significance) and cold spot areas (low–low significance) are dispersed. Meanwhile, in the map of 5 h, both the hot and cold spot areas are more connected and agglomerated. Detailed changes of the spatial features can be observed when the searching threshold increased from 2 to 5 h: the high–high agglomeration areas in the northwest extend eastward to Jiuquan, and westward to Aksu; the low–low clustering area surrounding Beijing–Tianjin–Hebei extended north along the Bohai Bay to Dalian; the low–low clustering area in southern Yunnan reached Sichuan.
(2) In the map of 2 h, there exists an intermixed trend between hot spot clusters and cold spot clusters. Meanwhile, in the map of 5 h, there is a spatial separation trend from hot-spot clusters to cold-spot clusters. From the 2 h map to the 5 h map, some local spatial clustered phenomenon disappeared, indicating that high–high or low–low characteristics were no longer significant ($p > 0.05$). For example, Shandong, southern Anhui, northern Jiangxi, and eastern Inner Mongolia experienced the disappearance of significance from high–high areas, while western Sichuan and western Hubei experienced it from low–low areas.
(3) As for the overall spatial differences between the northwest and the southeast, the map of 5 h reveals the overall differences more strongly than that of 2 h. From the 2 h map to the 5 h map, the high–high clustered areas tend to be distributed in the northwest rather than the southeast, whereas the low–low clustered areas present an opposite trend. The boundary zone between high–high clustered areas and low–low clustered areas becomes clearer, with more areas in the central region not being substantially agglomerated. In particular, several new high–high clusters emerged in Xinjiang and Gansu, and a new low–low clustered group emerged around Shanghai.

## 5. Discussion and Concluding Remarks

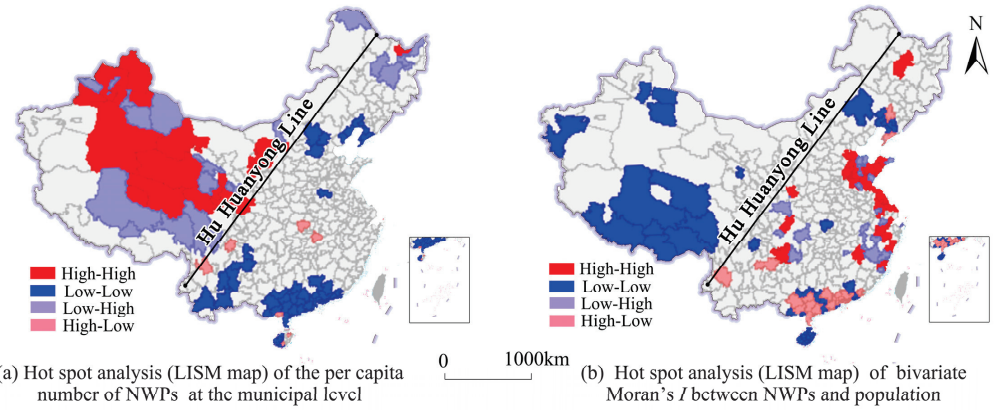
### *5.1. Discussion*

#### 5.1.1. Types and Distributions of NWPs

At the national scale, the distribution and development of water parks are frequently influenced by a number of factors, such as natural resources and ecological context, specific transportation locations, and urban, demographic, and socioeconomic factors [59]. Several studies have demonstrated that natural scenic locations are influenced by a variety of physical and cultural geographic factors, exhibiting a pattern of high density in the east and low density in the west along China's Hu Huanyong Line [60,61]. This study revealed that the spatial–temporal interaction between natural and human geographic factors in China contributed to the similar distribution patterns of NWPs. At the basin scale, diverse water management initiatives exhibited distinct distribution patterns affected by different local water resource endowments, which were tightly correlated with urban and regional development. Given that NWPs serve as a link between the natural environment and socioeconomic development, the standard deviation ellipse of NWP distribution can be used as an indicator for measuring the development of resource–population–city integrated systems and as a foundation for optimizing the allocation of water landscape resources.

5.1.2. Spatial Compatibility of NWP Resource and Population

Although the NWP kernel density was greater in the east than in the west, the accessibility of NWP resources was inverted. This indicates a spatial disparity between the total indicators (the kernel density of NWP resources) and per capita indicators (the accessibility of NWP resources). A local LISA (local indicators of hot spot analysis) map of the number of NWPs per capita (Figure 8a) and a local LISA map of the bivariate spatial autocorrelation between NWPs and population (Figure 8b) are compared to illustrate this issue. Figure 8a demonstrates a distribution pattern that closely resembles Figure 6b,e, with a high–high area clustered in the northwest and low concentrated in Beijing–Tianjin–Hebei, southern China, and the southwest. However, Figure 8b displays a more distinct pattern than Figure 6b,e, with the east coast and the west coast exhibiting high–high concentrations and low–low concentrations, respectively, in accordance with the general trend of high scenic density in the east and low scenic density in the west. The distribution of NWPs and populations indicates a match for the total quantity but a mismatch for the per capita volume, as revealed by these findings. From an algorithmic standpoint, the 2SFCA method measures the amount of a cumulative per capita resource accessed by individuals with border-unrestricted activities [62]. In the east of the Hu Huanyong Line, population concentrations were relatively stronger than those of NWPs, resulting in low–low areas in the corresponding position in Figure 6a–c, and high–high and high–low areas in the corresponding position in Figure 7d; in the west of the Hu Huanyong Line, population concentrations were relatively stronger than those of NWPs, resulting in high–high or low–high areas in the corresponding positions in Figure 7d.




(a) Hot spot analysis (LISM map) of the per capita number of NWPs at the municipal level

(b) Hot spot analysis (LISM map) of bivariate Moran's *I* between NWPs and population

**Figure 8.** Comparison of the hot-spot maps between different indicators.

5.1.3. The Influence of the Search Threshold on the Availability of NWP Resources

Searching thresholds have significant impacts on the spatial pattern of accessibility values [63], and a lower threshold is associated with a more pronounced spatial variation of the measured results. A higher threshold results into a spatial trend that is more continuous [64]. Our results were consistent with the aforementioned pattern. The accessibility calculated with a 2 h travel radius searching threshold was closer to a local indicator, which is appropriate for simulating short-distance travelling behavior. This finding facilitates the identification of local variations in accessibility values. Accessibility calculated with a 5 h travel radius searching threshold corresponded more closely to a global indicator, making it suitable for simulating long-distance travel and revealing a stronger clustering pattern, with a concentration of high–high accessibility in northwest China and low–low accessibility in south China and southwest China.

5.1.4. The Limitations

This study has several limitations. First, the 2SFCA method can still be improved further. Depending on the resource quantity, the servicing scope of NWPs varies, as does the maximum travel radius of individuals in cities with differing degrees of economic

development. Future studies are encouraged to integrate a variable searching threshold into the 2SFCA algorithm. Second, the time–space network between NWPs and cities is constructed based on a multi-level highway system as the basic data, without considering the combination of railway and aviation networks, which to some extent affects the accessibility measurement. Lastly, this research is limited to a case study in China and lacks exploration on other cases elsewhere in the world. A validation study comparing various regions at a global scale may be needed in the future.

### *5.2. Conclusions*

An NWP is a high-level utilization of water resources and a social development product. For a particular water conservation facility to develop into a NWP, it must first ensure its own engineering functions (such as flood control, irrigation, or drought resistance); then, it must have the potential to be an ecotourism destination with cultural, social, or historic heritage values, and it must also improve its management level to be approved by the Ministry of Water Resources. The evaluation of NWPs' spatial distribution and accessibility is crucial for maximizing their economic, social, and environmental benefits, which is compatible with sustainability principles such as comprehensive usage of resources and the resource-utilization-capacity improvement of traditional practices. The following are the general conclusions:

(1) Measuring the distribution of NWPs is an efficient method for determining the spatial pattern of typical water projects with high ecotourism value and the degree of comprehensive utilization of water resources at the national scale. Rich in water resources with enhanced regulations for water management, densely populated, highly urbanized, and with a convenient transportation network, the NWP agglomeration areas share similar regional characteristics. The spatial consistency between NWPs, river morphology, population, cities, and transportation is a consequence of the interaction between natural geographical factors and social-economic geographical factors, and will serve as a guide for sustainable regional planning.

(2) NWPs can function as detectors of various endowment and management modes of basin-scale water resources. As each category of NWPs developed from the corresponding water project, it became crucial to determine which water projects should be prioritized for upgrading to new NWPs and where. The optimal arrangement of the six categories of NWPs can not only optimize the allocation of water management resources, but also promote regional growth. Using existing examples as a guide, WLD-Type NWPs should be located in the middle or lower portions of rivers for optimal wetland utilization. URL-Type NWPs should concentrate around major cities along the regional development axis to coordinate urbanization; NRL-Type NWPs should be located near primary streams to serve as critical protecting nodes for important rivers and to generate sufficient ecological flow; RES-Type NWPs should be located in secondary main streams or tributaries to achieve the multipurpose utilization of medium- or small-sized reservoirs. The distribution patterns of WSC-Type and IRA-Type NWPs are not readily apparent and require additional investigation.

(3) The accessibility of NWPs is an effective indicator of the degree to which scenic water resources and population distribution are spatially matched. The map of accessibility values is spatially auto-correlated and unevenly agglomerated, which can be identified by the ESDA-generated LISA map and quantitatively evaluated by Moran's *I*. According to the characteristics of the map of accessibility, the NWPs should be viewed as a series of systematic source locations that provide both ecological and socioeconomic benefits for the surrounding area. Universal suggestions can be made in order to achieve equity in the allocation of NWP resources and to prevent the overdevelopment of water tourism. In areas where accessibility is high–high, there is little need to create new NWPs; however, the socioeconomic benefits can be enhanced by increasing the popularity and capacity of existing NWPs as tourist destinations to attract out-of-town visitors. Both the content and quantity of NWP must be enhanced

in the low-accessibility regions. In addition, some typical water facilities near urban areas can be transformed into new NWPs to attract local and short-distance visitors. In regions with high–low, low–high, or insignificant accessibility characteristics, the NWP systems should adopt a more diversified development strategy and form alliances with other types of natural scenic areas, aiming for a balance between social, economic, and environmental objectives.

**Author Contributions:** Conceptualization, C.Z.; methodology, C.Z.; software, C.Z. and C.G.; validation B.H.; formal analysis, B.H.; investigation, W.L.; resources, C.Z.; data curation, C.G.; writing—original draft preparation, C.Z.; writing—review and editing, C.Z. and B.H.; visualization, W.L.; supervision, B.H.; project administration, W.L.; funding acquisition, C.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Natural Science Foundation of Henan Province (grant number 232300421402); Youth Fund project for Humanities and Social Science Research of the Chinese Ministry of Education (grant number 22YJCZH047); Planning research project for Philosophy and Social Science of Henan Province (grant number 2020CZH007, 2022CSH040) and Annual Project of Philosophy and Social Sciences Planning in Henan Province (grant number 2022BJJ022).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Francois, B.; Schlef, K.E.; Wi, S.; Brown, C. Design considerations for riverine floods in a changing climate—A review. *J. Hydrol.* **2019**, *574*, 557–573. [CrossRef]
2. Jiang, Y. China's water scarcity. *J. Environ. Manag.* **2009**, *90*, 3185–3196. [CrossRef] [PubMed]
3. Wang, M.; Zhang, D.; Su, J.; Dong, J.; Tan, S. Assessing hydrological effects and performance of low impact development practices based on future scenarios modeling. *J. Clean. Prod.* **2018**, *179*, 12–23. [CrossRef]
4. Xu, X.; Tan, Y.; Yang, G. Environmental impact assessments of the Three Gorges Project in China: Issues and interventions. *Earth-Sci. Rev.* **2013**, *124*, 115–125. [CrossRef]
5. Sun, X.; Xiong, S.; Zhu, X.; Zhu, X.; Li, Y.; Li, B. A new indices system for evaluating ecological-economic-social performances of wetland restorations and its application to Taihu Lake Basin, China. *Ecol. Model.* **2015**, *295*, 216–226. [CrossRef]
6. Branche, E. The multipurpose water uses of hydropower reservoir: The SHARE concept. *Comptes Rendus Phys.* **2017**, *18*, 469–478. [CrossRef]
7. Averitt, E.; Steiner, F.; Yabes, R.A.; Patten, D. An assessment of the Verde River Corridor Project in Arizona. *Landsc. Urban Plan.* **1994**, *28*, 161–178. [CrossRef]
8. Reynaud, A.; Lanzanova, D. A global meta-analysis of the value of ecosystem services provided by lakes. *Ecol. Econ.* **2017**, *137*, 184–194. [CrossRef]
9. Armatas, C.; Venn, T.; Watson, A. Understanding social–Ecological vulnerability with q-methodology: A case study of water-based ecosystem services in wyoming, USA. *Sustain. Sci.* **2017**, *12*, 105–121. [CrossRef]
10. Shao, J.; Zhou, Y.; Luo, H.; Wang, J.; Zhang, Q. Comparative analysis of visual amenity services valuation: A nationwide assessment through propensity scoring matching and hedonic regression. *J. Environ. Manag.* **2023**, *325*, 116564. [CrossRef]
11. Meyerhoff, J.; Klefoth, T.; Arlinghaus, R. The value artificial lake ecosystems provide to recreational anglers: Implications for management of biodiversity and outdoor recreation. *J. Environ. Manag.* **2019**, *252*, 109580. [CrossRef] [PubMed]
12. Mácová, K.; Kozáková, Z. How Important for Society Is Recreation Provided by Multi-PurposeWater Reservoirs Welfare Analysis of the Vltava River Reservoir System. *Water* **2023**, *15*, 1966. [CrossRef]
13. Li, T.; Gao, X. Ecosystem Services Valuation of Lakeside Wetland Park beside Chaohu Lake in China. *Water* **2016**, *8*, 301. [CrossRef]
14. Satz, D.; Gould, R.K.; Chan, K.M.A.; Guerry, A.; Norton, B.; Satterfield, T.; Halpern, B.S.; Levine, J.; Woodside, U.; Hannahs, N.; et al. The challenges of incorporating cultural ecosystem services into environmental assessment. *AMBIO* **2013**, *42*, 675–684. [CrossRef] [PubMed]
15. Santarém, F.; Campos, J.C.; Pereira, P.; Hamidou, D.; Saarinen, J.; Brito, J.C. Using multivariate statistics to assess ecotourism potential of water-bodies: A case-study in mauritania. *Tour. Manag.* **2018**, *67*, 34–46. [CrossRef]
16. Liu, J.; Zang, C.; Tian, S. Water conservancy projects in China: Achievements, challenges and way forward. *Glob. Environ. Chang.* **2013**, *23*, 633–643. [CrossRef]

17. Ministry of Water Resources. *The Evaluation Standard of Water Park SL 300—2013*; China WaterPower Press: Beijing, China, 2013.
18. Li, W.; Qi, J.; Huang, S.; Fu, W.; Zhong, L.; He, B.-J. A pressure-state-response framework for the sustainability analysis of water national parks in China. *Ecol. Indic.* **2021**, *131*, 108127. [CrossRef]
19. Perry, D.; Harrison, I.; Fernandes, S.; Burnham, S.; Nichols, A. Global Analysis of Durable Policies for Free-Flowing River Protections. *Sustainability* **2021**, *13*, 2347. [CrossRef]
20. Liu, W.; Chen, W.; Cao, Y. The Evolution of theWaterfront Utilization and Sustainable Development of the Container Ports in the Yangtze River: A Case Study of the Yangtze River Delta. *Land* **2023**, *12*, 778. [CrossRef]
21. Cheung, D.; Tang, B. Social order, leisure, or tourist attraction? The changing planning missions for waterfront space in Hong Kong. *Habitat Int.* **2015**, *47*, 231–240. [CrossRef]
22. Qi, J.; Ding, L.; Lim, S. Application of a decision-making framework for multi-objective optimisation of urban heat mitigation strategies. *Urban Clim.* **2023**, *47*, 101372. [CrossRef]
23. Zhang, M.; Huang, Y.; Shen, S.; Ye, Y.; Liao, Q.; Wang, W.; Liu, L.; Zhu, X.; Guo, J. Study on the protection and sustainable development of scenic resources-a case study of Qingxiushan scenic spot in Nanning city. *J. Nat. Conserv.* **2023**, *72*, 126348. [CrossRef]
24. Yuan, D.; Wu, R.; Li, D.; Zhu, L.; Pan, Y. Spatial PatternsCharacteristics and InfluencingFactors of Cultural Resources in theYellow River National Cultural Park, China. *Sustainability* **2023**, *15*, 6563. [CrossRef]
25. Scott, D.; Lemieux, C. Climate change and protected area policy and planning in Canada. *For. Chron.* **2005**, *81*, 696–703. [CrossRef]
26. Lin, J.; Yang, W.; Yu, K.; Geng, J.; Liu, J. Construction of Water Corridors for Mitigation of Urban Heat Island Effect. *Land* **2023**, *12*, 308. [CrossRef]
27. Zheng, W.; Dong, W.; Lin, G. Adaptive management of estuarine resource utilization and wetland conservation based on multi-temporal remote sensing: A case study of Minjiang Estuary, China. *J. Nat. Conserv.* **2022**, *70*, 126286. [CrossRef]
28. Cheng, S.; Zhai, Z.; Sun, W.; Wang, Y.; Yu, R.; Ge, X. Research on the Satisfaction of Beijing Waterfront Green Space Landscape Based on Social Media Data. *Land* **2022**, *11*, 1849. [CrossRef]
29. Elomri, A.; Mazzoni, A.; Triki, C. ALiterature Review on SystemDynamics Modeling for SustainableManagement of Water Supply and Demand. *Sustainability* **2023**, *15*, 6826.
30. Wang, H. Preliminary investigation of waterfront redevelopment in Chinese coastal port cities: The case of the eastern Dalian port areas. *J. Transp. Geogr.* **2014**, *40*, 29–42. [CrossRef]
31. Qi, J.; Ding, L.; Lim, S. A decision-making framework to support urban heat mitigation by local governments. *Resour. Conserv. Recycl.* **2022**, *184*, 106420. [CrossRef]
32. Yang, Y.; Yao, C.; Xu, D. Ecological compensation standards of national scenic spots in western China: A case study of Taibai Mountain. *Tour. Manag.* **2020**, *76*, 103950.1–103950.17. [CrossRef]
33. Nesticò, A.; Maselli, G. Sustainability indicators for the economic evaluation of tourism investments on islands. *J. Clean. Prod.* **2020**, *248*, 119217. [CrossRef]
34. Meyer, N.; Schafft, M.; Wegner, B.; Wolter, C.; Arlinghaus, R.; Venohr, M.; von Oheimb, G. A day on the shore: Ecological impacts of non-motorised recreational activities in and around inland water bodies. *J. Nat. Conserv.* **2021**, *64*, 126073. [CrossRef]
35. Alic, E.; Trottier, L.; Twardek, W.M.; Bennett, L.L.; Chisholm, S.; Tremblay, P.; Tuononen, E.; Bennett, J.R.; Bower, S.D.; Lennox, R.J.; et al. Recreational fisheries activities and management in national parks: A global perspective. *J. Nat. Conserv.* **2021**, *59*, 125948. [CrossRef]
36. Scheepens, A.; Vogtländer, J.; Brezet, J. Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable. *J. Clean. Prod.* **2016**, *114*, 257–268. [CrossRef]
37. Robledano, F.; Esteve, M.; Calvo, J.; Martínez-Paz, J.M.; Farinós, P.; Carreño, M.F.; Soto, I.; Avilés, M.; Ballesteros, G.A.; Martínez-Baños, P.; et al. Multi-criteria assessment of a proposed ecotourism, environmental education and research infrastructure in a unique lagoon ecosystem: The Encanizadas del Mar Menor (Murcia, SE Spain). *J. Nat. Conserv.* **2018**, *43*, 201–210. [CrossRef]
38. Qi, J.; Lin, E.S.; Tan, P.Y.; Roger, C.M.H.; Sia, A.; Olszewska-Guizzo, A.; Zhang, X.; Waykool, R. Development and application of 3D spatial metrics using point clouds for landscape visual quality assessment. *Landsc. Urban Plan.* **2022**, *228*, 104585. [CrossRef]
39. Jalilian, M.; Salmanmahiny, A.; Danehkar, A.; Shayesteh, K. Developing a method for calculating conservation targets in systematic conservation planning at the national level. *J. Nat. Conserv.* **2021**, *64*, 126091. [CrossRef]
40. Rylands, A.; Brandon, K. Brazilian protected areas. *Conserv. Biol.* **2005**, *19*, 612–618. [CrossRef]
41. Abell, R.; Harrison, I.J. A boost for freshwater conservation. *Science* **2020**, *370*, 38–39. [CrossRef]
42. Li, P.; Shen, M.; Perry, D.; Li, C.; Zhao, M.; Yang, P. A comparative study on the spatial distribution characteristics and the driving factors of protected river systems between China and the United States of America. *Ecol. Indic.* **2022**, *135*, 108505. [CrossRef]
43. Duan, T.; Feng, J.; Chang, X.; Li, Y. Evaluation of the effectiveness and effects of long-term ecological restoration on watershed water quality dynamics in two eutrophic river catchments in Lake Chaohu Basin, China. *Ecol. Indic.* **2022**, *145*, 109592. [CrossRef]
44. Chu, C.; Chou, Y. Using cellular data to analyze the tourists' trajectories for tourism destination attributes: A case study in Hualien, Taiwan. *J. Transp. Geogr.* **2021**, *96*, 103178. [CrossRef]
45. Reitsamer, B.; Brunner-Sperdin, A.; Stokburger-Sauer, N. Destination attractiveness and destination attachment: The mediating role of tourists' attitude. *Tour. Manag. Perspect.* **2016**, *19*, 93–101. [CrossRef]
46. Wen, C.; Albert, C.; Haaren, C.V. Equality in access to urban green spaces: A case study in hannover, germany, with a focus on the elderly population. *Urban For. Urban Green.* **2020**, *55*, 126820. [CrossRef]

47. Furze, J.N.; Eslamian, S.; Raafat, S.; Swing, K. *Mathematical Advances towards Earth Systems Protection and Sustainability*; Springer: Cham, Switzerland, 2022; Volume 1, 337p.
48. Li, W.; He, B.; Qi, J. Water Conservation Scenic Spots in China:Developing the Tourism Potential of Hydraulic Projects and Water Resources. *Sustainability* **2018**, *10*, 4509. [CrossRef]
49. Chen, Y.; Jin, F.; Lu, Y.; Chen, Z.; Yang, Y. Development history and accessibility evolution of landtransportation network in Beijing-Tianjin-Hebei region. *J. Geogr. Sci.* **2018**, *28*, 1500–1518. [CrossRef]
50. Brunsdon, C. Estimating probability surfaces for geographical point data: An adaptive kernel algorithm. *Comput. Geosci.* **1995**, *21*, 877–894. [CrossRef]
51. Dong, J.; Peng, J.; Liu, Y.; Qiu, S.; Han, Y. Integrating spatial continuous wavelet transform and kernel density estimation to identify ecological corridors in megacities. *Landsc. Urban Plan.* **2020**, *199*, 103815. [CrossRef]
52. Korpilo, S.; Virtanen, T.; Saukkonen, T.; Lehvävirta, S. More than A to B: Understanding and managing visitor spatial behaviour in urban forests using public participation GIS. *J. Environ. Manag.* **2018**, *207*, 124–133. [CrossRef]
53. Xing, L.; Liu, Y.; Liu, X.; Wei, X.; Mao, Y. Spatio-temporal disparity between demand and supply of park green space service in urban area of Wuhan from 2000 to 2014. *Habitat Int.* **2018**, *71*, 49–59. [CrossRef]
54. Cao, Y.; Guo, Y.; Zhang, M. Research on the Equity of Urban Green Park Space Layout Based on Ga2SFCA Optimization Method—Taking the Core Area of Beijing as an Example. *Land* **2022**, *11*, 1323. [CrossRef]
55. Wang, F. Measurement, optimization, and impact of health care accessibility: A methodological review. *Ann. Am. Assoc. Geogr.* **2012**, *102*, 1104–1112. [CrossRef]
56. Tobler, W.R. A Computer Movie Simulating Urban Growth in the Detroit Region. *Econ. Geogr.* **1970**, *46*, 234–240. [CrossRef]
57. Zhang, X.; Geng, Y.; Tong, Y.W.; Kua, H.W.; Tian, X.; Wu, R.; Zhao, X.; Chiu, A.S. Spatial characteristics and its driving factors of low-carbon energy technology innovation in China: A gravity movement and exploratory spatial data analysis. *J. Clean. Prod.* **2021**, *295*, 126481. [CrossRef]
58. Anselin, L.; Rey, S. Properties of Tests for Spatial Dependence in Linear Regression Models. *Geogr. Anal.* **1991**, *23*, 112–131. [CrossRef]
59. Ma, H.; Zou, J. Impacts of official high-standard scenic spots on environment and growth—Evidence from China's 5A scenic spots at the city level. *Ecol. Econ.* **2022**, *201*, 107555. [CrossRef]
60. Xu, J.; Wei, J.; Zhao, D. Influence of social media on operational efficiency of national scenic spots in china based on three-stage DEA model. *Int. J. Inform. Manag.* **2016**, *36*, 374–388. [CrossRef]
61. Huang, Y.; Lin, T.; Xue, X.; Zhang, G.; Liu, Y.; Zeng, Z.; Zhang, J.; Sui, J. Spatial patterns and inequity of urban green space supply in China. *Ecol. Indic.* **2021**, *132*, 108275. [CrossRef]
62. Page, N.; Langford, M.; Higgs, G. An evaluation of alternative measures of accessibility for investigating potential 'deprivation amplification' in service provision. *Appl. Geogr.* **2018**, *95*, 19–33. [CrossRef]
63. Knap, E.; Ulak, M.B.; Geurs, K.T.; Mulders, A.; van der Drift, S. A composite X-minute city cycling accessibility metric and its role in assessing spatial and socioeconomic inequalities—A case study in Utrecht, the Netherlands. *J. Urban Mobil.* **2023**, *3*, 100043. [CrossRef]
64. Wu, J.; Chen, H.; Wang, H.; He, Q.; Zhou, K. Will the opening community policy improve the equity of green accessibility and in what ways?—Response based on a 2-step floating catchment area method and genetic algorithm. *J. Clean. Prod.* **2020**, *263*, 121454. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*sustainability*

MDPI

*Article*

# How Do Spatial Forms Influence Psychophysical Drivers in a Campus City Community Life Circle?

**Shi-Ying Li [1], Zhu Chen [2], Lian-Huan Guo [1], Fangbing Hu [3], Yi-Jun Huang [1], Dan-Cheng Wu [1], Zhigang Wu [1,*] and Xin-Chen Hong [1,4,*]**

[1] School of Architecture and Urban-Rural Planning, Fuzhou University, Fuzhou 350108, China; 211520031@fzu.edu.cn (S.-Y.L.); lianhuan.guo@outlook.com (L.-H.G.)
[2] Institute of Environmental Planning, Leibniz University Hannover, Herrenhäuser Str. 2, 30419 Hanover, Germany; chen@umwelt.uni-hannover.de
[3] Department of Forest Resources Management, University of British Columbia, Vancouver, BC V6T 1Z4, Canada; fangbing.hu@outlook.com
[4] School of Architecture, Southeast University, Nanjing 210096, China
* Correspondence: klins@fzu.edu.cn (Z.W.); xch.hung@outlook.com (X.-C.H.)

**Abstract:** The physical environment of urban public facilities is an important driver for public health and work efficiency. Unfortunately, citizens are exposed to negative physical environments because of inappropriate spatial forms in urban growth boundaries. This study aims to explore psychophysical drivers and their spatial distribution in campus city community life circles during the COVID-19 pandemic. Questionnaires and measuring equipment were used to gather psychophysical information in a 15 min campus city community life circle in Fuzhou, China. To this end, acoustic, light and thermal environments were used to map spatial distributions. We then explored relationships between spatial form and psychophysical parameters. The study results show that the distance to road (DTR), green area ratio (GR) and street width (SW) are all potential spatial drivers for psychophysical information. Furthermore, the acoustical, light and thermal environments provide interactions for the public understanding of the environment. These findings contribute to the understanding and evaluation of psychophysical drivers, spurring regional industry in community life circles and contributing to developing suitable plans and industrial distribution in urban areas.

**Keywords:** urban public facilities; equal time circle; physical environment; community life circles

**Citation:** Li, S.-Y.; Chen, Z.; Guo, L.-H.; Hu, F.; Huang, Y.-J.; Wu, D.-C.; Wu, Z.; Hong, X.-C. How Do Spatial Forms Influence Psychophysical Drivers in a Campus City Community Life Circle? *Sustainability* **2023**, *15*, 10014. https://doi.org/10.3390/su151310014

Academic Editor: Robert Krzysztofik

Received: 13 May 2023
Revised: 19 June 2023
Accepted: 20 June 2023
Published: 24 June 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The urbanization process in China is currently experiencing a rapid development. However, this process has resulted in high-intensity development and rapid expansion that have significantly impacted the urban environment. This has triggered a series of urban diseases, such as the heat island effect, noise pollution, light pollution, air pollution, etc., which have seriously reduced the quality of the urban living environment. Multiple studies have focused on the elements of thermal, acoustic and light environments in urban areas, which indicate that poor urban physical environments can have a significant negative impact on people's physiological and mental health [1,2]. For instance, urban noise exposure may cause annoying moods and insomnia, increasing the probabilities of hypertension and cardiovascular disease, as well as negative effects on the auditory and nervous systems [3]. The urban thermal environment also poses a significant risk factor for death and related diseases in the population, especially cardiovascular and respiratory diseases, during heat waves [4,5]. Furthermore, the light environment directly affects not only the ambience of public spaces, but also people's behavior, sleep and mood [6]. These urban physical environments potentially influence public health in communities.

A community living circle is the basic constituent unit of urban space where most daily activities occur. In contrast to traditional communities, campus cities should integrate

the campus, community and industrial areas in a symbiotic and complementary way. Communities are an extension of commerce, residence and education within universities in the campus city, enriching the spatial pattern of the university town and promoting diversified development from traditional teaching spaces. At the same time, with the popularization of the concept of a "shared campus" and "shared community", sharing public facilities between campus city communities and universities has become an inevitable trend [7]. The sharing of sports facilities and resources has brought great convenience to the community. The Fuzhou city campus is rich in sports facility resources, and can serve social services and radiate sports activities of surrounding residents. It can also provide a sharing platform for staff and college students to effectively use venue resources and participate in sports activities. The outbreak of the COVID-19 pandemic changed public recreational and commercial activities in community living circles. During the pandemic period, residents' need for fitness and leisure increased, and sports facilities in university town communities became important public activity places for community residents, college teachers and students.

Against this backdrop, it is indispensable to provide suitable community utility services in community life circles, especially in emergency quarantines, contributing to building an urban organic system of healthy cities in terms of a healthy environment and a healthy society [8]. The quality indicators of a healthy city are derived from both the objective aspect, such as the average regional environmental noise, the land area of sports facilities per capita and greening coverage, and the subjective aspect, such as satisfaction with environmental quality [9].

This requires high-quality community public facilities to meet the needs of residents for their daily activities. Public activity spaces are a complex environment containing many factors, among which physical factors, such as the thermal environment [10], acoustic environment [11], visual environment, etc., can affect individual perception [12]; other factors can also affect individual perception, and can affect one another, influencing people's perception of the overall environment. Different factors jointly affect the physical environment, and many studies have focused on the relationship between physical environmental factors and environmental comfort, conducting research on thermal comfort and acoustic comfort [13,14]. A large body of research has also focused on the effects of noise and its sound pressure levels on individual thermal perception. Some scholars used the temperature and noise sound pressure level (SPL) in different durations to explore the subjective effects of the acoustic environment and thermal environment on people [15]. Some scholars also used the equivalent continuous sound pressure level (Leq) to study the relationship between the background soundscape and thermal environment, finding that noise is an important factor affecting thermal perception [16]. In a study of the perception of the visual environment, visual factors mainly included the surface materials, shadows and lights of buildings or roads [17,18]. Some scholars found that under different thermal environment conditions, solar light illumination (LUX) had a crossmodal effect on thermal sensation, which could alleviate the thermal discomfort in outdoor public spaces by improving visual comfort [19]. Therefore, public facilities, as important activity spaces of community life circles, should take environmental comfort as a necessary condition for outdoor activities, and comprehensively consider the influence of acoustic, light, thermal and other factors.

Notably, sports facilities are one of the most important types of public facilities in campus city community life circle, contributing benefits to physical fitness, the residents' health status, the efficiency of operations and buying inclination [20]. Plenty of studies have paid attention to the environments around urban stadiums, having become a topic of interest [21–23]. A previous piece of research explored the relationship between reverberation time, activity noise levels and human comfort in the acoustic environment of a stadium [1]. In addition, the typical thermal environment of a university gymnasium was effectively simulated based on the thermal building layout, building orientation, natural lighting and ventilation [24]. The gymnasium building form may affect thermal comfort in subtropical humid and hot regions, especially in summer [25]. Furthermore, internal relationships may exist among natural light, stadiums and visitor behavior from a combined subjective and

objective perspective [26]. However, there is a lack of the comprehensive consideration of acoustic, light and thermal environments and the visualization of psychophysical spatial distribution in stadiums in community living circles.

Thus, this study was conducted to fill the above gaps, aiming to: (1) explore the data interval for the best-perceived effects of environmental elements in the study area; (2) observe psychophysical relationships between acoustic, light and thermal environments; (3) and visualize the psychophysical drivers influencing spatial distribution through the use of a geographic information system (GIS).

## 2. Methods

### *2.1. Study Area and Observation Sites*

The study area was in Fuzhou, which is located on the southeastern coast of China, eastern Fujian, downstream of the Min River, at latitude 25°15′~26°39′ N and longitude 118°08′~120°31′ E. It is a central subtropical climate zone with warm winters and hot summers, high temperatures and heavy humidity, small annual and daily temperature differences, an average annual temperature range of 17° to 26° and an annual relative humidity of approximately 77%. The Fuzhou University City Sports Center is located in the central shared area of the University City in Minhou County, Fuzhou City (see Figure 1 left), covering an area of 2.9 hectares, with a 20,000-seat stadium, a 4000-seat gymnasium and a standard outdoor swimming pool, with a large area of green landscapes and rest facilities inside.

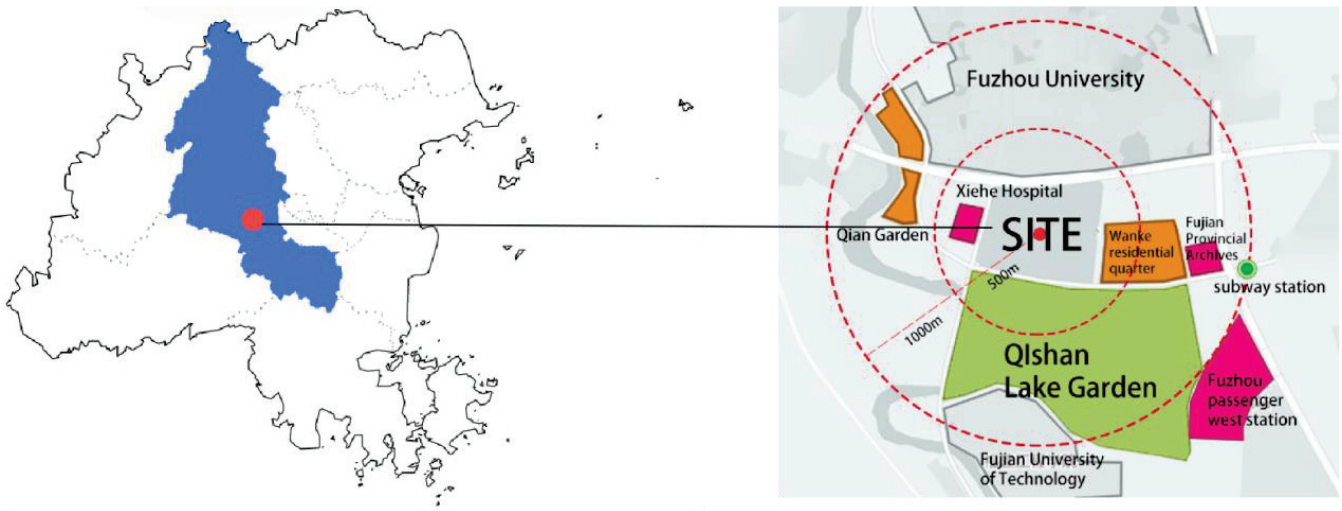



**Figure 1.** Location (**left**) and surrounding environment (**right**) of the university town sports center.

The sports center is adjacent to Fuzhou University to the north, Qishan Lake Park to the south and is 0.6 km from the subway station, making public transportation more convenient. The surrounding land is mainly occupied by residential areas, higher education institutions and green park spaces, with a small part occupied by public facilities and cultural facilities, such as hospitals and archives (see Figure 1, right). The main guests of the sports center are university students and surrounding residents. Although the number of events in the gymnasium decreased during the pandemic, the internal green square and sports facilities were still open for residents. Thus, the sports center was an important place for sports and leisure in the campus city community life circle during the pandemic.

The center point of the Fuzhou University City Sports Center was used as the origin of the campus city community life circle, with a 15 min walking circle from the origin in the study area. We divided the study area into several 100 × 100 m grids. The grids were required to occupy the full study area, and removed less than 50% grids in residents' movable spaces. Eighty-six observation sites were selected (see Figure 2). The gathering of physiological and soundscape information was conducted on sunny days (except for holi-

days) between 9:00 and 15:00 in October and December 2021, with an average temperature of 16–23 °C.

**Figure 2.** Research area and observation sites.

### *2.2. Gathering Subjective and Objective Data*

#### 2.2.1. Equipment Measuring

Acoustic environment parameters were gathered with type-1 sound level meters (Aihua Co., Ltd., made in China). The parameters included an equivalent sound pressure level ($L_{Aeq}$) and statistical noise level ($L_{90}$, $L_{50}$, $L_{10}$).

Light environment parameters were gathered with multifunctional environmental detectors. The illumination uniformity was the ratio of the minimum illuminance to the average illuminance on a given plane (sometimes the ratio to the maximum illuminance). We measured open space illumination ($E_n$) and ground reflection illumination ($E_w$). Then, we obtained the surface light environment coefficient, which was the ratio of $E_n$ to $E_w$ in external spaces.

Thermal environment parameters were gathered using multifunctional environmental detectors. The combination of temperature and humidity reflected the heat exchange between the human body and the surrounding environment. We measured the temperature (T) and humidity (f) at each observation site. Then, we obtained the temperature–humidity index (THL) and level division of the THL (see Table 1). Furthermore, the equation used for the THL was as follows:

$$THL = T - 0.55(1 - f)(T - 14.47) \quad (1)$$

**Table 1.** Level division of temperature–humidity index [27].

| THL | >28 | 27–28 | 25–26.9 | 17–24.9 | 15–16.9 | <15 |
|---|---|---|---|---|---|---|
| perception | burning hot | hot | warm | comfort | cool | cold |

Equation (1) is the evolution of the temperature and humidity index formula proposed by the Russian scholar Oliver. Its physical significance is the temperature after a humidity revision, which could be used as an index to comprehensively consider the influence of humidity and temperature on human comfort.

2.2.2. Questionnaire

This paper discusses the correlation mechanism of acoustic, light and thermal environment by analyzing the subjective satisfaction and the correlation between acoustic, light and thermal environments. In this study, the score of subjective satisfaction played the role of the dependent variable, while the equivalent traffic noise level (Leq), surface illumination uniformity, external space surface light environment coefficient and temperature and humidity index were a group of independent variables. The analysis of independent variables and dependent variables established a subjective satisfaction model about the physical environment of the university town sports center; the model was verified. The subjective satisfaction (psychological) data were collected through the use of a questionnaire survey, measuring the physical data in a grid. The questionnaire was randomly distributed and given to university town sports center facility residents and pedestrians. It was used to assess the subjective satisfaction of the respondents to the acoustic a thermal environments. Each grid included at least two questionnaires, which represented each grid including at least two more respondents.

The questionnaire included two parts. The first part was about the satisfaction of the acoustic, light and thermal environments, as well as a satisfaction evaluation of the natural environment (the allocation of flowers, plants and trees, the natural landscape, etc.) and overall environment. They were graded according to a Likert scale, which is commonly a 4-, 5- or 7-point order scale that respondents use to rate the extent to which they agree or disagree with a statement [28]. In this study, the questionnaire was scored from 1 to 5, with participants being enquired about perceived satisfaction: not satisfying at all (+1), slightly satisfying (+2), moderately pleasant (+3), very satisfying (+4) and extremely satisfying (+5). The second part asked respondents to select the most important physical environmental indicators that they believed affected their willingness to stay, including the noise, quiet, hot, cold, brightness and dimness. To reduce the discrete subjective evaluation data to the same order of magnitude, the subjective evaluation scores were normalized to between 0 and 1. Table 2 shows the content of the questionnaire containing the Likert scale used in this study.

**Table 2.** Questionnaires on the acoustic, light and thermal environments around the University Town Sports Center.

| Question | Likert Scale [28] 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1.How satisfied are you with the surrounding acoustic environment?<br>2. How are you satisfied with the surrounding light environment?<br>3.How are you satisfied with the surrounding thermal environment?<br>4.How satisfied are you with the surrounding natural environment?<br>5.How satisfied are you satisfied with the transportation around you?<br>6. How satisfied are you with your overall environment? | Far from satisfied | Not very satisfied | General | More satisfied | Very satisfied |
| 7. Do you think the hot environment has an impact on your current willingness to stay?<br>8. Do you think the cold environment has an impact on your current willingness to stay?<br>9. Do you think a quiet environment will affect your current willingness to stay?<br>10. Do you think the noisy environment will affect your current willingness to stay?<br>11. Do you think the bright environment will affect your current willingness to stay?<br>12. Do you think the dark environment will have an impact on your current willingness to stay? | No impact | Less impact | Have an impact | Greater impact | Significant impact |

A total of 268 questionnaires were collected with 243 valid responses. The recovery efficiency was 90.7%. The age distribution of the respondents ranged from 18 to 65 years old, with a high proportion of people aged 18–34 years old, with respondents mostly being college students. In terms of the gender ratio, there were 132 females and 111 males. The reliability and validity of the questionnaire were analyzed using SPSS 24.0 software. The results showed that the alpha reliability coefficient was 0.860, and the KMO number was 0.83 ($p < 0.05$). The questionnaire had good reliability and validity.

2.2.3. Spatial Form Indicators

To explore the relationship between the spatial factors and subjective and objective environmental indicators, we selected the spatial environmental factors that could best reflect the spatial and environmental characteristics of the campus city community life circle,

including three dimensions of land cover, block road network and population density. The land cover dimension included the three indicators building density (BD), green space ratio (GR) and water area ratio (WR). The road network dimension included the three indicators distance to the road (DTR), street width (SW) and road density (RD). The population density dimension included a POI point (commerce, catering, office, etc.).

GIS 10.2 software was used to statistically analyze the above indicators. We used the building surface layer to calculate the different grids' construction land, green spaces and water cover areas. The measuring tool was used to calculate the distance from the measuring point to the motorway, the street width and the total length of the road in the grid. The road density was the ratio of the road length to the grid area. The number of POI points in different grids was calculated through spatial connection. The indexes of spatial environmental factors in the regional grid were studied, and the correlation between physical measurement indexes, subjective perception indexes and spatial environmental factor indexes was analyzed.

### *2.3. Statistical Analyses*

We visualized the spatial distribution of psychophysical parameters using GIS. The Kriging method was used to visualize the spatial distribution in ArcGIS 10.2 [29]. Land use types and areas in the grids were systematically clustered using the hierarchical cluster analysis (HCA), which was carried out in SPSS 24. Furthermore, we conducted both regression and Spearman's rho analysis to explore the relationships between psychophysical and spatial drivers, which was carried out in Originl2021.

## 3. Results

### *3.1. Spatial Distribution of Environmental Drivers*

Our results showed that $L_{Aeq}$ ranged from 58.12 to 84.92 dB, presenting with a large fluctuation, and the overall average value was 67.71 dB, with 58% exceeding 70 dB. Previous research showed that it is difficult to talk in an environment with a sound level of 70 dB, suggesting a noisy and active environment [30]. We also found that foreground sound ($L_{10}$) ranged from 60.18 to 89.57 dB, and background sound ($L_{90}$) ranged from 39.52 dB to 75.64 dB, indicating various sound sources in this study area. Furthermore, we combined Figures 3–5 to explore spatial distribution characteristics more specifically.

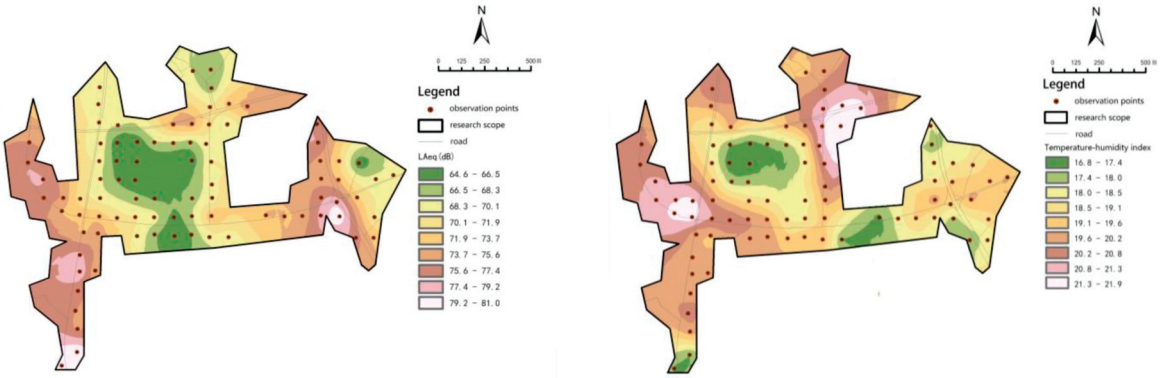



**Figure 3.** Spatial distribution of $L_{Aeq}$ (**left**) and temperature–humidity index (**right**).

Figure 3 (left) shows the visualization of $L_{Aeq}$. From the spatial distribution, the equivalent sound pressure level near the University City Sports Center was the lowest, followed by the northern side of Qishan Lake Park and the living area of Fuzhou University. From the perspective of spatial distribution, the sound pressure level was greatly affected by the roads, surrounding land and population flow. The interval of the temperature–humidity index was [16, 22], indicating that the overall human feeling was relatively comfortable. Figure 3 (right) shows the spatial distribution of the temperature–humidity index. The temperature–humidity index in the sports center region was the lowest, followed

by the value in the eastern region. The temperature–humidity index of the southwest and northeast of the sports center was the highest, and the maximum peak appeared in the road intersection grid. The overall temperature–humidity indexes were within the comfortable interval values, and the changes in different temperature–humidity indexes may have been affected by the measurement time, green space distribution and road density.

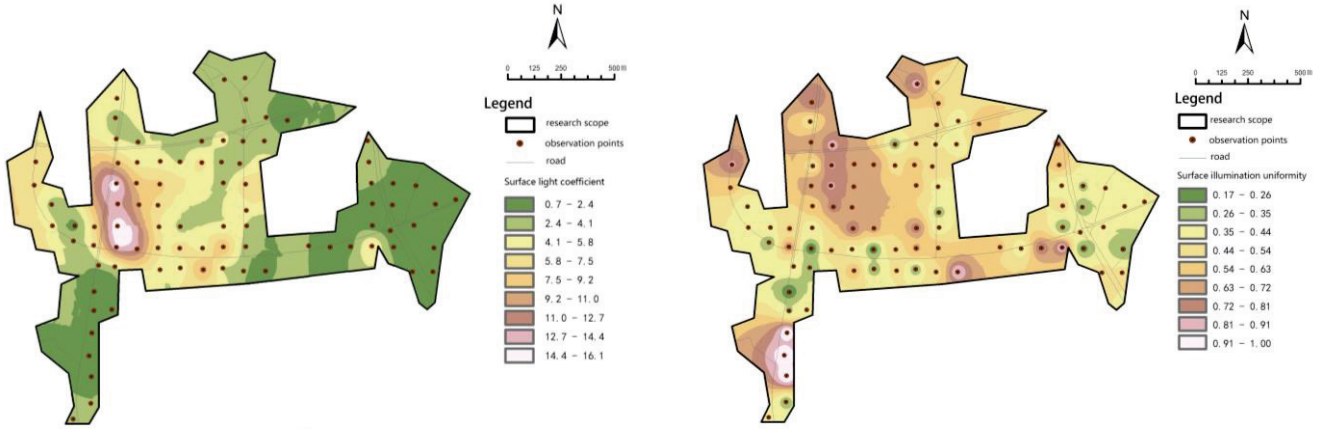



**Figure 4.** Spatial distribution diagram of surface light coefficient in outdoor space (**left**) and surface illumination uniformity (**right**).

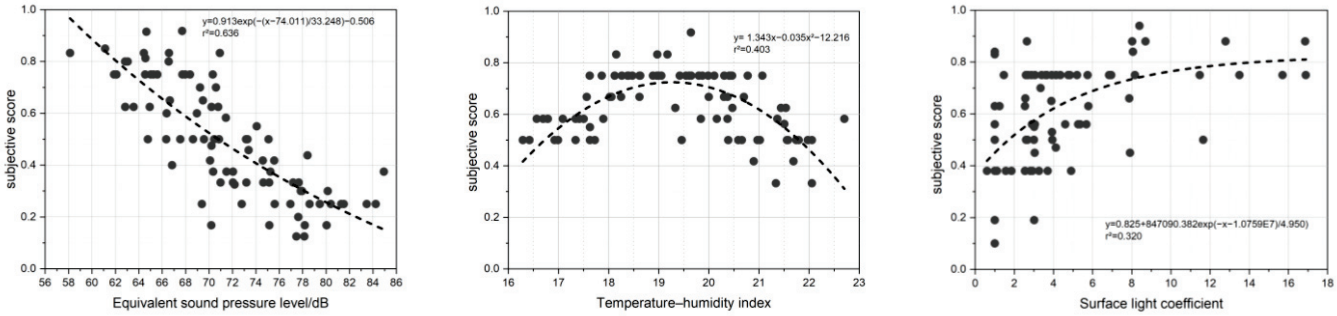



**Figure 5.** Regression curve of physical environment indicators and public satisfaction.

The interval in the surface light coefficient in the outdoor space was [1, 16.2]. Figure 4 (left) shows the spatial distribution of the light environment coefficient, showing obvious high-value areas. The area with the largest coefficient was the west side of the sports center along the road, followed by the south side along the road. The results showed that the optical coefficients of the eastern and southwestern regions furthest from the sports center were the lowest. The interval of the surface illumination uniformity in the study area was [0.2, 1], which was concentrated within [0.4, 0.7]. Figure 4 (right) shows the spatial distribution of the surface illumination uniformity. The high values of illumination uniformity were distributed in the sports center and its northwest side, Qishan Lake Park and southwest side near the riverbank. The results showed that the lowest value of illumination uniformity was distributed on the east side of the road.

### *3.2. Psychological Tendency of Public in Campus City Community Life Circle*

#### 3.2.1. Willingness to Stay

A multiple-response analysis was conducted on the results of six indicators related to the acoustic, light and thermal environments in a 15 min community life circle, which potentially affected willingness to stay for the public. We divided thermal environment indicators into cold and hot, acoustic environment indicators into noisy and silent and light environment indicators into bright and dim. The public responded with the willingness to stay through these six indicators. The results showed that the probability of willingness to

stay was 29.90%, 16.90%, 24.10%, 10.10%, 9.00% and 10.00%, respectively. This suggested that the degree of coldness influenced the probability of willingness to stay in the space, followed by loudness and heat degree. These findings could potentially suggest that the willingness to stay was influenced by environmental perception.

#### 3.2.2. Threshold and Interval Relationships between Environmental Drivers and Satisfaction of Environments

Figure 5 (left) shows the relationship between $L_{Aeq}$ and the satisfaction of the acoustic environment through an exponential function curve. The results showed that the satisfaction of the acoustic environment gradually decreased with $L_{Aeq}$ increasing, with the satisfaction values ranging from 0.1 to 1.0. The satisfaction values exceeded 0.8 when $L_{Aeq}$ was below 62 dB; the satisfaction values ranged from 0.5 to 0.8 when $L_{Aeq}$ ranged from 62 dB to 70 dB.

Figure 5 (middle) shows the relationship between the temperature–humidity index and the satisfaction values through polynomial curve fitting. The results showed that the satisfaction value was above 0.6 when the interval of the temperature–humidity index was [17.5, 21.5]. The satisfaction value tended to reach an optimal value when the temperature–humidity index reached 19.3. Furthermore, the satisfaction values showed a decreasing trend when the temperature–humidity index was higher than 21.5 and lower than 17.5.

Figure 5 (right) shows the relationship between satisfaction of surface light coefficient and outdoor space light environment coefficient through an exponential function curve. The results also showed that the satisfaction value tended to play a positive role in the light environment coefficient. The overall range of surface illumination uniformity fluctuated from 0.2 to 1.0, with satisfaction values concentrating in a range from 0.5 to 0.6.

These results suggested the effect of other potential drivers between environmental parameters and satisfaction, which suggested a need to also consider analyzing the correlation of these drivers.

### *3.3. Construction of the Environmental Satisfaction Prediction Model*

#### 3.3.1. Model Summary

To reveal the relationships between the environmental satisfaction and physical indicators, this study needed to construct a prediction model of environmental satisfaction and determine five assumptions, as shown below.

**H1.** *The equivalent sound pressure level has a certain relationship with the overall environmental satisfaction.*

**H2.** *The temperature and humidity index is related to the overall satisfaction of the environment.*

**H3.** *The surface light coefficient of external space has a certain relationship with the overall environmental satisfaction.*

**H4.** *There is a certain relationship between the illumination uniformity and the overall environment satisfaction.*

**H5.** *There is a relationship between age and overall environment satisfaction.*

To test the correctness of the five hypotheses H1, H2, H3, H4 and H5, a multiple linear regression analysis was performed in the SPSS 24.0 software. The coefficient of determination ($R^2$) between the final multiple linear regression model and the independent variables (noise, temperature and humidity index, light coefficient, illumination uniformity and age) and the dependent variable was obtained.

Firstly, to test the correctness of hypothesis H5 of this study, a correlation analysis was used to explore the relationship between age and the overall satisfaction of the environment. The Spearman's correlation analysis structure showed that age was not significantly associated with light, heat and the overall environment, but was associated with the acoustic environment satisfaction ($p < 0.01$) (Table 3). This indicated that the subjective satisfaction with the acoustic environment decreased with increasing age; the reason may be that the

elderly are more sensitive to surrounding traffic noise, while young people are relatively more inclusive of the noise. Thus, the younger the respondents were, the less vulnerable they were to noise interference.

**Table 3.** Age and environmental satisfaction correlation analysis.

| | | | Age and Environmental Satisfaction Correlation Analysis | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Age** | **Sound Environment Satisfaction** | **Light Environment Satisfaction** | **Thermal Environment Satisfaction** | **Overall Environmental Satisfaction** |
| Spearman Rho | Age | correlation coefficient | 1.000 | −0.207 ** | 0.002 | −0.018 | −0.079 |
| | | significance | 0.000 | 0.001 | 0.974 | 0.777 | 0.199 |

** At the 0.01 level, the correlation was significant, Sig. (2-tailed).

An analysis of variance (ANOVA) is a statistical method used to test for differences between two or more averages [31]. In the relationship between illumination uniformity and overall environmental satisfaction, the analysis of variance showed that there was no significant relationship between illumination uniformity and overall environmental satisfaction (Table 4). Therefore, for the independent variables "respondent age" and "illumination evenness", the two independent variables were ignored in the dependent variable "overall satisfaction".

**Table 4.** ANOVA of illumination uniformity and overall satisfaction evaluation.

| **ANOVA [a]** | | | | | | |
|---|---|---|---|---|---|---|
| **Model** | | **Sum of Squares** | **df** | **Mean Square** | **F** | **Sig.** |
| 1 | Regression | 0.267 | 1 | 0.267 | 0.532 | 0.468 [b] |
| | Residual | 41.606 | 83 | 0.501 | | |
| | Total | 41.873 | 84 | | | |

[a] Dependent variable: overall satisfaction evaluation. [b] Predictors: (constant) surface illumination uniformity.

To further demonstrate the relevance of these three models, in Table 5, we tested three different regression models using the stepwise method. Table 5 shows the variance test results of the overall satisfaction evaluation model. The model included the equivalent sound pressure level, temperature and humidity index and external surface space light coefficient. In the model, Sig, the equivalent sound pressure level, temperature and humidity index and surface light coefficient had a 0.000 ($p < 0.01$) confidence interval (CI) of 0.99, indicating that the three physical indicators were significantly related to the overall environmental satisfaction and could be used as predictors of the environmental satisfaction prediction model.

**Table 5.** Results of analysis of variance (ANOVA).

| **ANOVA [a]** | | | | | | |
|---|---|---|---|---|---|---|
| **Model** | | **Sum of Squares** | **df** | **Mean Square** | **F** | **Sig.** |
| 1 | Regression | 9.158 | 1 | 9.158 | 20.890 | 0.000 [b] |
| | Residual | 36.387 | 83 | 0.438 | | |
| | Total | 45.546 | 84 | | | |
| 2 | Regression | 11.141 | 2 | 5.571 | 13.277 | 0.000 [c] |
| | Residual | 34.404 | 82 | 0.420 | | |
| | Total | 45.546 | 84 | | | |
| 3 | Regression | 20.190 | 3 | 6.730 | 21.499 | 0.000 [d] |
| | Residual | 25.356 | 81 | 0.313 | | |
| | Total | 45.546 | 84 | | | |

[a] Dependent variable: overall satisfaction evaluation. [b] Predictors: (constant) equivalent sound pressure level. [c] Predictors: (constant) equivalent sound pressure level and humidity–temperature index. [d] Predictors: (constant) equivalent sound pressure level, humidity–temperature index and surface light coefficient.

3.3.2. Coefficients and the Final Model

According to the column "Unstandardized coefficient (B)" in Table 6, the final multiple linear regression model (Model 3) was as follows:

$$\text{Overall satisfaction evaluation} = 7.509 - 0.321 \text{ equivalent sound pressure level} - 0.195 \text{ temperature and humidity index} + 0.456 \text{ surface light coefficient of external space.} \quad (2)$$

R = Pearson's correlation coefficient = 0.666.

$R^2$ = coefficient of determination (R Square) = 0.443.

**Table 6.** Regression coefficients and statistical tests using stepwise method for three models.

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 7.317 | 0.874 | | 8.376 | 0.000 |
| | Equivalent sound pressure level | −0.056 | 0.012 | −0.448 | −4.571 | 0.000 |
| 2 | (Constant) | 8.883 | 1.118 | | 7.948 | 0.000 |
| | Humidity–temperature index | −0.096 | 0.044 | −0.211 | −2.174 | 0.033 |
| | Equivalent sound pressure level | −0.052 | 0.012 | −0.416 | −4.284 | 0.000 |
| 3 | (Constant) | 7.509 | 0.999 | | 7.518 | 0.000 |
| | Equivalent sound pressure level | −0.040 | 0.011 | −0.321 | −3.749 | 0.000 |
| | Humidity–temperature index | −0.089 | 0.038 | −0.195 | −2.324 | 0.023 |
| | Surface light coefficient | 0.090 | 0.017 | 0.456 | 5.376 | 0.000 |

The equivalent sound pressure level $L_{Aeq}$ (10 min) was expressed in decibels, dBA. The temperature in the temperature–humidity index was the ambient temperature in degrees Celsius, and the relative humidity was the ambient relative humidity expressed as a percentage. The optical environment coefficient of external space was the ratio of open space lighting (En) to ground reflection lighting (Ew) in external space, %.

In Equation (2), the value of the variable "external space surface light coefficient" was 0.456, which was the highest coefficient among the independent variables. Therefore, the surface light coefficient was the most effective predictor of overall environmental satisfaction, followed by the equivalent sound pressure level, with a coefficient of 0.321, and, finally, the greenhouse index with a coefficient of 0.195. This was different from the existing literature results, which may have been due to the small range of temperature and humidity values in the survey time of this study. Based on these findings, the influence of light and acoustic environments was shown to be relatively prominent. This means that during the autumn and winter season when the climate is more suitable, to improve people's satisfaction with the sound, light and thermal environments of the overall open space, more attention should be paid to the surface light coefficient to ensure a good experience of the light environment, and traffic noise should be reduced as much as possible.

### *3.4. Correlations between Environmental Drivers and Human Satisfaction of Environments*

We performed a Spearman analysis of the correlation between acoustic, light and thermal physical index measurements and satisfaction with the acoustic, thermal and light environments. Figure 6 shows that overall environmental satisfaction was significantly positively correlated with satisfaction with the acoustic, light and thermal environments, with the highest correlation for satisfaction with the acoustic environment ($p < 0.01$). In addition, among the correlations between subjective and objective data, overall environmental satisfaction was positively correlated with light coefficient and negatively correlated with the temperature–humidity index and $L_{Aeq}$, suggesting that these drivers played a role in overall environmental perception.

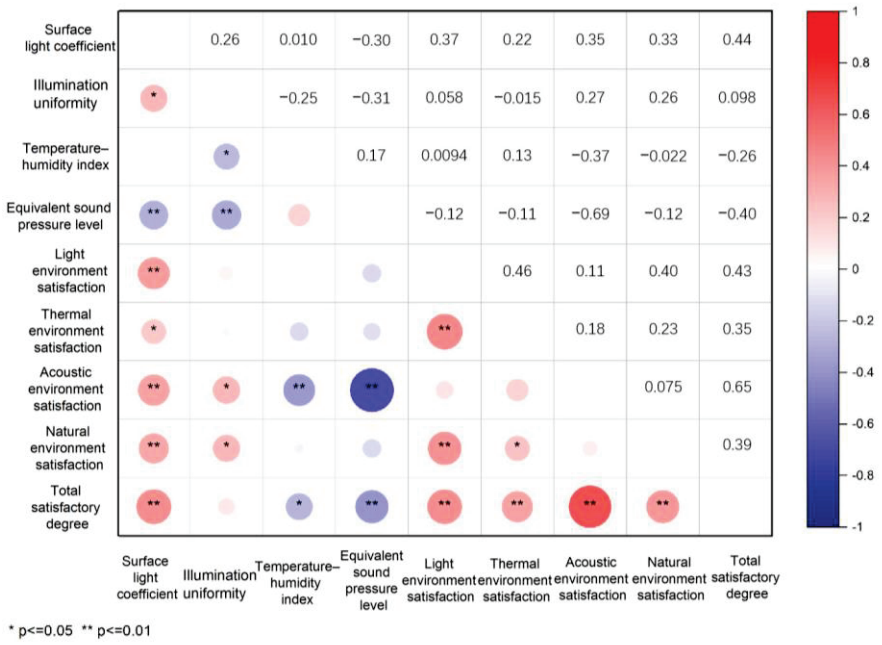



**Figure 6.** Correlation analysis between satisfaction and physical parameters.

The results showed that natural environment satisfaction was positively correlated with the light coefficient and illumination uniformity, suggesting a potential impact influenced by natural elements such as natural plant landscapes. Additionally, natural environment satisfaction had positive correlations with Light environment and thermal environment satisfaction, suggesting the positive influence of natural plant landscapes on vision. Acoustic environment satisfaction was negatively correlated with the temperature–humidity index and $L_{Aeq}$.

Furthermore, there was a negative correlation between the temperature–humidity index and illumination uniformity. Our findings also showed that $L_{Aeq}$ was negatively correlated with illumination uniformity and light drivers. The high value of illumination uniformity was potentially due to spatial features with green vegetation, contributing to a dampening effect on $L_{Aeq}$. These results suggested the need to consider analyzing impact drivers for the surrounding spatial environment.

### *3.5. Impact Drivers of Spatial Forms*

#### 3.5.1. Cluster Analysis of Different Land Types

In order to explore the relationship between psychological and environmental elements of sound, light and thermal environments, as well as spatial elements, this study explored the current situation of the region. Plots of different land types often have different physical space and environmental characteristics, which may have different effects on psychology. Therefore, this study conducted a cluster analysis according to the divided land type of each grid and tried to explore the spatial elements affecting the acoustic, light and thermal environmental indicators. First, we conducted a cluster analysis using SPSS based on the area data of various land types within the grid, resulting in four types of land use: clusters A, B, C and D (see Figure 7). The results showed that cluster A was dominated by green spaces and surface water; cluster B was dominated by roads and green spaces; cluster C was dominated by roads and buildings; cluster D was a mixture of three types of roads, buildings and green spaces.

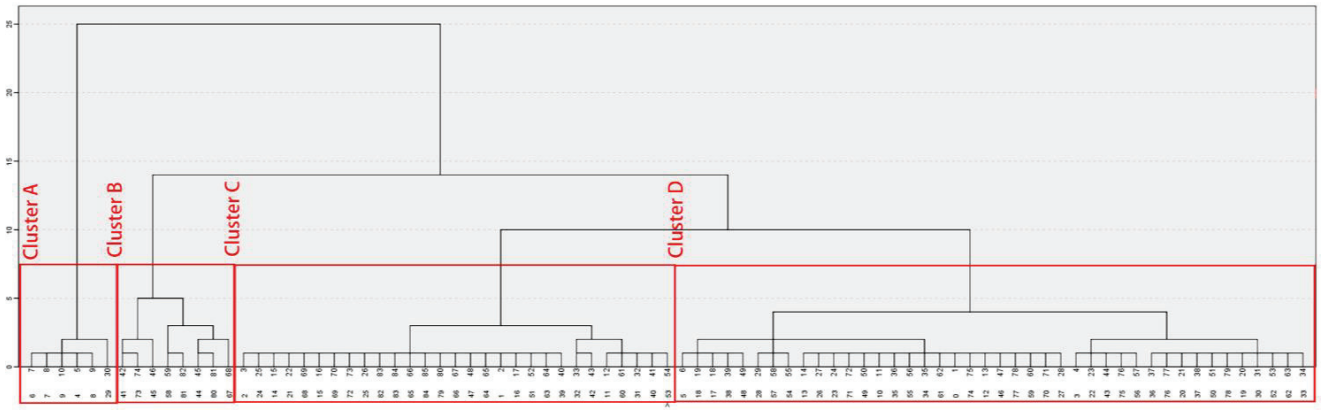



**Figure 7.** HCA of land use areas.

Figure 8 shows the physical conditions of different land use types. The results suggest that there were significant differences in the values of acoustic, light and thermal indicators corresponding to different site types. The site types with the highest values for the temperature–humidity index were roads and buildings, while the lowest were green spaces and water, with the difference between the remaining two site types being small. The site types with the highest mean value of surface illumination uniformity were green space and surface water, with the difference between the remaining three types not being significant, and the lowest were roads, buildings and green spaces.

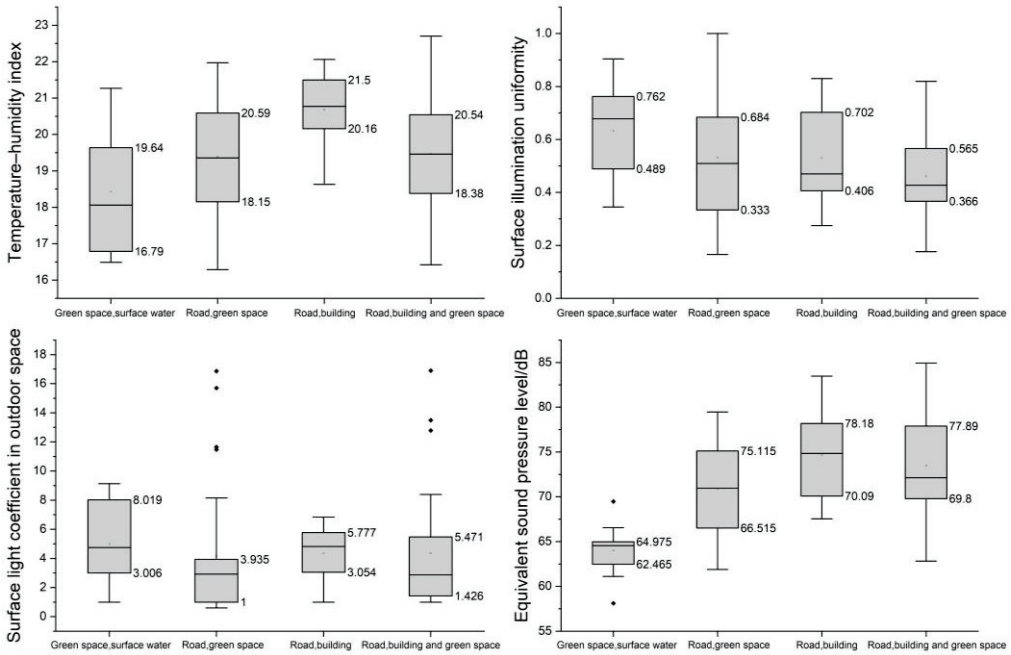



**Figure 8.** Physical conditions of different land use types.

Furthermore, our findings suggested that the site types with the highest value for the surface light coefficient in outdoor space were green space and surface water, while the lowest were roads and green spaces. There were some outliers in both road and green space land use and road, building and green space land use. The site type with the highest $L_{Aeq}$ was road and building land use, and the lowest was green space and surface water land use, with a mean difference of 10.6 dB for roads and green spaces. The values for buildings, roads and green spaces were not very different, and were all higher than for green spaces and surface water, indicating that roads had a greater influence on the sound pressure level.

We also performed a statistical analysis of the subjective satisfaction values for the four types of land use. Through the use of an analysis of variance, the overall environmental satisfaction among the four types of land was shown to be significantly different ($p < 0.05$), except for thermal environment satisfaction ($p > 0.05$). The numerical distributions of acoustic, light, heat and overall environmental satisfaction are shown in Table 7. From the average value of the data, the differences in light, sound and overall environmental satisfaction among the four land use types were large, except for the thermal environment (see Table 8). This may have been due to the small difference between the temperature and humidity index of all types of land, and the thermal environment was not significant in scale, being only 100 m, so there was no significant difference in the thermal environment satisfaction of all types of land. The overall satisfaction of green spaces and water areas was the highest. Among them, the satisfaction of the acoustic environment and optical environment was far higher than that of the other three types of land. It could be preliminarily judged that the positive influence of green spaces or water bodies on the satisfaction of the acoustic environment and light environment was significant. Road and green space land use had the lowest light environment, acoustic environment and overall environmental satisfaction, followed by road and building land use and road, building and green space land use. It could be preliminarily judged that the negative impact of roads or building on the satisfaction of the acoustic environment and light environment was relatively significant.

**Table 7.** Environmental satisfaction of different land use types.

| | Land Type | Mean Value | Standard Deviation | Standard Error | Min | Max |
|---|---|---|---|---|---|---|
| Light environment satisfaction | green space and surface water | 4.28 | 0.25 | 0.10 | 4.00 | 4.67 |
| | road and green space | 3.47 | 0.60 | 0.21 | 2.50 | 4.25 |
| | road and building | 3.75 | 0.44 | 0.08 | 3.00 | 4.33 |
| | road, building and green space | 3.68 | 0.45 | 0.07 | 3.00 | 4.50 |
| Thermal environment satisfaction | green space and surface water | 3.89 | 0.27 | 0.11 | 3.33 | 4.00 |
| | road and green space | 3.53 | 0.40 | 0.14 | 3.00 | 4.00 |
| | road and building | 3.55 | 0.48 | 0.09 | 2.50 | 4.33 |
| | road, building and green space | 3.56 | 0.64 | 0.09 | 2.00 | 5.00 |
| Sound environment satisfaction | green space and surface water | 4.17 | 0.28 | 0.11 | 4.00 | 4.66 |
| | road and green space | 2.52 | 0.68 | 0.24 | 1.67 | 3.50 |
| | road and building | 2.66 | 0.87 | 0.17 | 1.00 | 4.33 |
| | road, building and green space | 3.07 | 1.05 | 0.16 | 1.00 | 5.00 |
| Overall environmental satisfaction | green space and surface water | 3.78 | 0.62 | 0.25 | 3.00 | 4.33 |
| | road and green space | 2.80 | 0.52 | 0.18 | 2.00 | 3.75 |
| | road and building | 3.23 | 0.68 | 0.13 | 2.00 | 4.00 |
| | road, building and green space | 3.41 | 0.71 | 0.11 | 1.67 | 5.00 |

**Table 8.** ANOVA of environmental satisfaction of different land use types.

| ANOVA | | | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|---|---|
| Light environment satisfaction | interblock | (assemble) | | 2.464 | 3 | 0.821 | 3.991 | 0.010 |
| | | linear term | Unweighted | 1.217 | 1 | 1.217 | 5.913 | 0.017 |
| | | | weighting | 0.624 | 1 | 0.624 | 3.030 | 0.085 |
| | | | deviation | 1.840 | 2 | 0.920 | 4.471 | 0.014 |
| Thermal environment satisfaction | interblock | (assemble) | | 0.638 | 3 | 0.213 | 0.687 | 0.563 |
| | | linear term | Unweighted | 0.505 | 1 | 0.505 | 1.632 | 0.205 |
| | | | weighting | 0.241 | 1 | 0.241 | 0.777 | 0.381 |
| | | | deviation | 0.397 | 2 | 0.199 | 0.641 | 0.529 |
| Sound environment satisfaction | interblock | (assemble) | | 13.345 | 3 | 4.448 | 5.085 | 0.003 |
| | | linear term | Unweighted | 5.287 | 1 | 5.287 | 6.044 | 0.016 |
| | | | weighting | 0.514 | 1 | 0.514 | 0.587 | 0.446 |
| | | | deviation | 12.832 | 2 | 6.416 | 7.334 | 0.001 |
| Overall environmental satisfaction | interblock | (assemble) | | 4.003 | 3 | 1.334 | 2.900 | 0.040 |
| | | linear term | Unweighted | 0.242 | 1 | 0.242 | 0.527 | 0.470 |
| | | | weighting | 0.104 | 1 | 0.104 | 0.226 | 0.636 |
| | | | deviation | 3.899 | 2 | 1.949 | 4.238 | 0.018 |

#### 3.5.2. Relationship between Spatial and Psychophysical Drivers

Below, we further explored which spatial elements caused differences in physical indicators and subjective satisfaction between different land uses. The indicators of each spatial element in different grids were analyzed and counted using GIS. We conducted a Spearman analysis for each of their corresponding spatial element indicators. The spatial data characteristics of the measurement grids are shown in Table 9.

**Table 9.** Data characteristics of grid space elements.

| | Average | Standard Deviation | Minimum | Maximum |
|---|---|---|---|---|
| Green space ratio (GR) | 0.532 | 0.297 | 0.126 | 1.000 |
| Building density (BD) | 0.069 | 0.150 | 0.000 | 0.680 |
| Water ratio (WR) | 0.031 | 0.103 | 0.000 | 0.685 |
| Distance to road (DTR) m | 39.077 | 43.545 | 0.920 | 230.760 |
| Road density (RD) km/km$^2$ | 5.297 | 4.910 | 0.000 | 12.700 |
| Street width (SW) m | 26.341 | 14.561 | 0.000 | 45.000 |
| Number of POI points (POIs) | 2.106 | 3.071 | 0.000 | 13.000 |

Figure 9 shows that there were more spatial element factors that affected the satisfaction of the acoustic environment. The spatial element factors had the highest negative correlation with two indicators of the street network, SW and RD, followed by BD and POI. This result indicated that traffic factors had an impact on the perception of the acoustic environment. The larger the road width and the higher the road grade, the higher the driving speed and traffic flow of cars, contributing to the generation of traffic noise and, therefore, having a negative impact on the acoustic environment experience.

The spatial element factor positively correlated with the subjective evaluation of the thermal environment, and the subjective evaluation of the light environment was GR, which indicated that green space positively influenced the experience of the thermal and light environments. Our findings also showed that overall satisfaction was correlated with several spatial factors, except for water bodies, indicating that all three dimensions of spatial environmental factors of land cover, road network and population density had an impact on the overall environmental perception. There may be a potential reason for the low degree of landscape development and utilization of water bodies and the small size of water bodies.

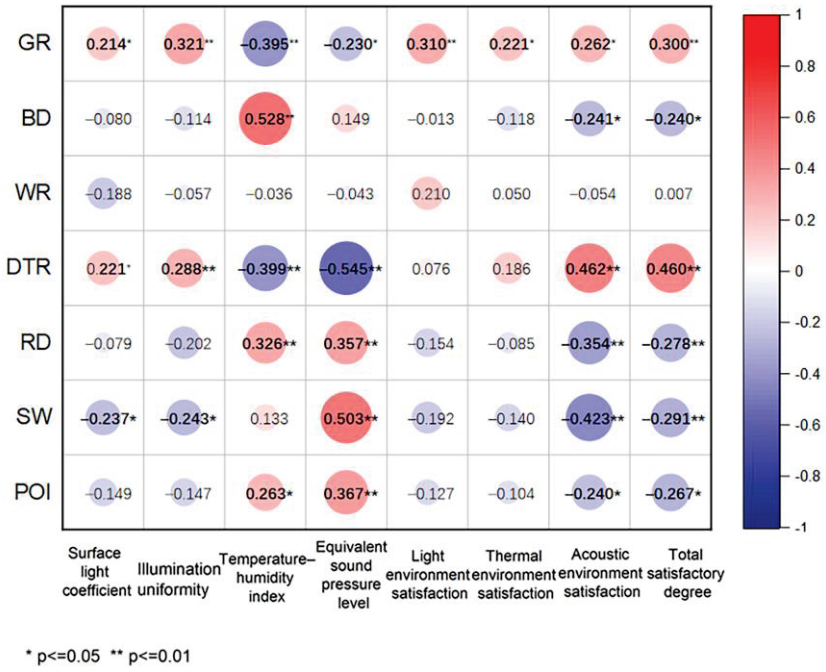



**Figure 9.** Correlation between spatial factors and subjective and objective indicators.

In the correlation analysis between the objective physical indicators and spatial factors, $L_{Aeq}$ was positively correlated with RD, SW and POI, and negatively correlated with DTR and GR. We found that the biggest effect on $L_{Aeq}$ was neighborhood road network factors. The temperature–humidity index was negatively correlated with DTR and GR, and positively correlated with BD, RD and POI. Furthermore, the values of the temperature–humidity index were influenced by roads, buildings and green spaces.

The light coefficient was positively correlated with GR and DTR, and negatively correlated with SW. More greenery and vegetation had a shading effect on solar illumination, and more greenery coverage was obtained away from the road. The large width of the road contributed to a weaker shading effect for surrounding buildings and green belts, which may have led to an increase in solar radiation intensity and a small ratio of sky illumination to surface illumination. Illumination uniformity was positively correlated with GR and negatively correlated with SW and DTR, which was similar to the results of the light coefficient. The illumination uniformity positively contributed to visual perception, such as green space, improving visual comfort, while roads contributed negatively to visual perception.

## 4. Discussion

The acoustic, light and thermal environment physical indicators in the urban environment affected the psychological feelings of respondents. In the overall environmental satisfaction evaluation, the equivalent sound pressure level, the greenhouse index and the external space surface light coefficient together affected the overall environmental satisfaction evaluation, with the external space surface light coefficient having the largest proportion, followed by the equivalent sound pressure level, which was mainly affected by road traffic noise pollution in this study.

Roads as potential drivers contributed to high $L_{Aeq}$ levels in the western and eastern parts of the study areas located along Metro Line 2 in the southeast, which contained denser residential areas and construction sites with negative auditory perception. There were low $L_{Aeq}$ areas near the campuses, parks and sports centers, which were less affected by road noise and had high subjective scores. Building density and POI facility points contributed to an increase in human and vehicle traffic, especially around public service facilities in the community living circle. Additionally, various activity sounds intertwined with natural

sounds and peripheral traffic sounds to perform various rhythmic soundscapes [32–34]. Natural sounds, such as flowing water, wind, vegetation movement and birdsong were positive drivers influencing human perception, while human-generated activity sounds and traffic sounds were negative drivers [35]. We observed correlations between spatial and psychophysical drivers. DTR and GR positively correlated with the satisfaction of the acoustic environment, suggesting that the experience of the acoustic environment significantly improved when the public was away from road noise, and the area with a larger proportion of green space was less influenced by traffic, with green space having a certain barrier effect on traffic noise [36]. Our findings suggested the proportion of natural and biological sounds in green space was high, and that of artificial sound was low, contributing to improving the auditory experience. In urban green spaces, increasing natural soundscapes and reducing traffic noise could improve auditory satisfaction and levels of human health [37,38]. Previous research suggests that these positive effects of urban green spaces are directly related to the objective reduction in noise levels to the subjective perception of noise exposure [39]. Furthermore, the results suggested a significant correlation with POI points, where dense service points were also accompanied by greater crowd density, generating a concomitant increase in the proportion of activity and traffic sound.

Our findings suggested that the temperature–humidity index showed higher values close to roads with low greenery and high building densities, and a high percentage of green spaces and water bodies contributed lower values. Plant elements, such as trees, shrubs and turf, had a shading effect on the public spaces, contributing to reducing direct sunlight and external heat reflection through plant transpiration and improving the surrounding microclimate. There was a positive effect of building density on surface temperature in high-density urban built-up areas on the thermal environment, contributing to environmental warming [40,41]. This suggested a need for a certain increase in green space ratio to improve vegetation transpiration capacity and to enhance local convection, contributing to reducing the temperature–humidity index [42]. Road density levels were positively correlated with the average road temperature [43].

In the urbanization process, urban green spaces with low surface temperatures were transformed into other land use types with high surface temperatures, thus, negatively affecting the urban thermal environment [44,45]. The design of green spaces should be fully considered in the design of urban public facility spaces to mitigate the thermal environment problems. Our findings suggested a positive correlation between POI points and the temperature–humidity index because most of the POI points were for commercial services and public facilities, with high values in terms of building density and road density. Previous research suggests that areas of commercial buildings and alleys are important drivers for the increase in surface temperature [46]. In addition, dense POI points contributes to high temperature–humidity indexes.

Furthermore, the results suggested a high correlation between the light and thermal environments, both of which correlated with the spatial elements of green spaces. Landscape elements, such as vegetation configuration and the vignette arrangement of green spaces, improved the visual experience and microclimate, contributing to improving the satisfaction of the light environment. Previous research suggested that relevant elements of green spaces positively influence the subjective evaluation of human audiovisuals, and audiovisual satisfaction increased when the share of green-related elements was higher than that of traffic-related elements [47]. Considering warm winters and cool summers for climate characteristics of Fuzhou, the shading effect of green spaces plays a positive role in light and thermal environments. Therefore, the design and planning of green spaces should be considered in the construction of the physical environment of public facilities in Fuzhou. Suitable design and planning could contribute to improving the physical environment comfort, enhancing the efficiency of operations and vitality of business forms.

## 5. Conclusions

We used subjective questionnaires and objective physical measures to determine the effect of spatial forms on psychophysical perception. Spatial forms affected psychophysical drivers in the community life circle. The physical indicators of the acoustic, light and thermal environments in the urban environment affected the psychological feelings of the respondents. Our findings showed that: (1) The acoustic, light and thermal environments had an impact on overall environmental perception. The light coefficient, $L_{Aeq}$ and temperature–humidity index were important environmental indicators that affected the overall environmental satisfaction. (2) The $L_{Aeq}$ and temperature–humidity index of roads and construction land were opposite to those of green spaces and water bodies. (3) Green spaces played a positive role in the satisfaction of acoustic, light and thermal environments. (4) The density of roads, buildings and POIs played a negative role on satisfaction with the acoustic environment. (5) Green spaces and street width potentially influenced the light coefficient and surface illumination uniformity.

Our findings contribute to the basic data of urban public facilities and spatial physical environment evaluations. Exploring the impact of spatial factors on the psychophysical environment allowed us to understand which design elements in urban planning can provide higher comfort in public spaces and develop suitable suggestions for low-carbon planning and industrial distribution in urban areas. In addition to the acoustic, light and thermal environments, the comfort and satisfaction of community public spaces were also affected by other factors, including physiology, social culture, behavior, etc. The driving role of more factors on the psychophysical environment should be considered comprehensively in future studies.

**Author Contributions:** Conceptualization, S.-Y.L.; methodology, X.-C.H.; software, D.-C.W.; formal analysis, L.-H.G.; investigation, S.-Y.L.; data curation, X.-C.H.; writing—original draft preparation, S.-Y.L. and X.-C.H.; writing—review and editing, Z.C. and F.H.; visualization, Y.-J.H. and S.-Y.L.; supervision, Z.W. and X.-C.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors appreciate the valuable comments of editors and anonymous reviewers. This project was supported by the National Natural Science Foundation of China (grant no. 52208052), the Program of Humanities and Social Science Research of the Ministry of Education of China (grant no. 21YJCZH038) and the Fujian Natural Science Foundation, China (grant no. 2021J01639, 2023J05108).

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Al-Arja, O.A. Acoustic Environment and Noise Exposure in Fitness Halls. *Appl. Sci.* **2020**, *10*, 6349. [CrossRef]
2. Deng, L.; Luo, H.; Ma, J.; Huang, Z.; Li, X. Effects of integration between visual stimuli and auditory stimuli on restorative potential and aesthetic preference in urban green spaces. *Urban For. Urban Green.* **2020**, *53*, 126702. [CrossRef]
3. Basner, M.; Babisch, W.; Davis, A.; Brink, M.; Clark, C.; Janssen, S. Auditory and non-auditory effects of noise on health. *Lancet* **2014**, *383*, 1325–1332. [CrossRef]
4. Chun, B.; Hur, M.; Won, J. Impacts of Thermal Environments on Health Risk: A Case Study of Harris County, Texas. *Int. J. Environ. Res. Public Health* **2021**, *18*, 5531. [CrossRef] [PubMed]
5. Eramitsoglou, I.; Daglis, I.A.; Amiridis, V.; Chrysoulakis, N.; Paganini, M. Evaluation of satellite-derived products for the characterization of the urban thermal environment. *J. Appl. Remote Sens.* **2012**, *6*, 061704. [CrossRef]
6. Englund, A.; Partonen, T. Mode of action of light and its significance for health. *Duodecim Lääketieteellinen Aikakauskirja* **2009**, *125*, 609–616.
7. Abdelaal, M.S.; Abdelaal, D. Towards an innovative community: Rethinking the urban configuration of the university campus within new cities. In *New Cities and Community Extensions in Egypt and the Middle East: Visions and Challenges*; Springer: Cham, Switzerland, 2019; pp. 237–256.
8. Noriko, H.; Kiyoko, H. A study of urban green open space for organic waste recycling. *Environ. Syst. Res.* **2004**, *32*, 101–109.
9. de Leeuw, E. Healthy Cities. In *Handbook of Settings-Based Health Promotion*; Springer International Publishing: Cham, Switzerland, 2022; pp. 91–104.
10. Lai, D.; Zhou, C.; Huang, J.; Jiang, Y.; Long, Z.; Chen, Q. Outdoor space quality: A field study in an urban residential community in central China. *Energy Build.* **2014**, *68*, 713–720. [CrossRef]

11. Jin, Y.; Jin, H.; Kang, J. Combined effects of the thermal-acoustic environment on subjective evaluations in urban squares. *Build. Environ.* **2020**, *168*, 106517. [CrossRef]
12. Geng, Y.; Hong, B.; Du, M.; Yuan, T.; Wang, Y. Combined effects of visual-acoustic-thermal comfort in campus open spaces: A pilot study in China's cold region. *Build. Environ.* **2022**, *209*, 108658. [CrossRef]
13. de Dear, R.J.; Akimoto, T.; Arens, E.A. Progress in thermal comfort research over the last twenty years. *Indoor Air* **2013**, *23*, 442–461. [CrossRef]
14. Yu, L.; Kang, J. Modeling subjective evaluation of soundscape quality in urban open spaces: An artificial neural network approach. *J. Acoust. Soc. Am.* **2009**, *126*, 1163–1174. [CrossRef] [PubMed]
15. Candas, V.; Pellerin, N. Effects of steady-state noise and temperature conditions on environmental perception and acceptability. *Indoor Air* **2010**, *14*, 129–136.
16. Tsai, K.-T.; Lin, Y.-H. Identification of urban park activity intensity at different thermal environments and visible sky by using sound levels. *Int. J. Biometeorol.* **2018**, *62*, 1987–1994. [CrossRef]
17. Rosso, F.; Pisello, A.L.; Cotana, F.; Ferrero, M. On the thermal and visual pedestrians' perception about cool natural stones for urban paving: A field survey in summer conditions. *Build. Environ.* **2016**, *107*, 198–214. [CrossRef]
18. Samira, L.; Saliha, A.; Sigrid, R. Effect of vegetation cover on thermal and visual comfort of pedestrians in urban spaces in hot and dry climate. *Nat. Technol.* **2017**, *17*, 30–42.
19. Lam, C.K.C.; Yang, H.; Yang, X.; Liu, J.; Ou, C.; Cui, S.; Kong, X.; Hang, J. Cross-modal effects of thermal and visual conditions on outdoor thermal and visual comfort perception. *Build. Environ.* **2020**, *186*, 107297. [CrossRef]
20. Sang, A.L.; Ju, Y.J.; Lee, J.E.; Hyun, I.S.; Jin, Y.N.; Han, K.T. The relationship between sports facility accessibility and physical activity among Korean adults. *BMC Public Health* **2016**, *16*, 1244–1253.
21. Kiuri, M.; Teller, J. Olympic stadiums in their urban environment: A question of design and cultural significance. *J. Cult. Herit. Manag. Sustain. Dev.* **2012**, *2*, 115–129. [CrossRef]
22. Dilalos, S.; Alexopoulos, J.D.; Tsatsaris, A. Calculation of building correction for urban gravity surveys. a case study of Athens metropolis (Greece). *J. Appl. Geophys.* **2018**, *159*, 540–552. [CrossRef]
23. Twardowski, M. Football stadiums—Icons of sports architecture. *Tech. Trans.* **2018**, *11*, 53–70. [CrossRef]
24. Ma, B.; Wang, D. The Analysis and Optimal Design for Thermal Environment of Gymnasium. *Adv. Mater. Res.* **2011**, *368*, 3682–3687. [CrossRef]
25. Huang, X.; Zhang, Q.; Wang, Z.; Ma, X. Thermal sensation under high-intensive exercise in naturally ventilated gymnasiums in hot-humid areas of China: Taking basketball players for example. *Indoor Built Environ.* **2022**, *31*, 139–154. [CrossRef]
26. Liu, Y.; Yu, G.; Zheng, S. Gymnasium Natural Light Environment Optimization Design Oriented by Environment-Behavior Studies. *Adv. Mater. Res.* **2013**, *831*, 223–227. [CrossRef]
27. Steadman, R.G. The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science. *J. Appl. Meteorol. Climatol.* **1979**, *18*, 861–873. [CrossRef]
28. Sullivan, G.M.; Artino, A.R. Analyzing and interpreting data from Likert-type scales. *J. Raduate Med. Educ.* **2013**, *5*, 541–542. [CrossRef] [PubMed]
29. Childs, C. Interpolating surfaces in ArcGIS spatial analyst. *ArcUser July–Sept.* **2004**, *3235*, 32–35.
30. Morillas, J.M.B.; González, D.M.; Gozalo, G.R. A review of the measurement procedure of the iso 1996 standard. relationship with the European noise directive. *Sci. Total Environ.* **2016**, *565*, 595–606. [CrossRef]
31. Lane, D.M. Analysis of Variance. 2013. Available online: https://onlinestatbook.com/2/analysis_of_variance/ANOVA.html (accessed on 19 June 2023).
32. Zhang, R.; Zhu, L.; Zhang, Y. Investigation on the restoration effect of soundscape in parks in high-density cities: Taking Lu Xun Park in Shenyang, China as an example. In Proceedings of the 23rd International Congress on Acoustics, Aachen, Germany, 9–13 September 2019; pp. 876–883.
33. Hong, X.-C.; Liu, J.; Wang, Y.-S. Soundscape in Urban Forests. *Forests* **2022**, *13*, 2056. [CrossRef]
34. Chen, Z.; Zhu, T.-Y.; Liu, J.; Hong, X.-C. Before Becoming a World Heritage: Spatiotemporal Dynamics and Spatial Dependency of the Soundscapes in Kulangsu Scenic Area, China. *Forests* **2022**, *13*, 152. [CrossRef]
35. Jing, C.; Li, S.; Cao, S.; Ma, X. Study on influencing factors and influencing strength of urban green space relieving heat island effect—Taking Beijing as an example. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *601*, 012033. [CrossRef]
36. Mueller, W.; Steinle, S.; Prkk, J.; Parmes, E.; Liedes, H.; Kuijpers, E. Health effects of greenspace on outdoor physical activity and indoor pm2.5 and noise: A case study of four European cities. *Environ. Epidemiol.* **2019**, *3*, 277.
37. Payne, S.R. Urban park soundscapes and their perceived restorativeness. *Proc. Inst. Acoust.* **2010**, *32*, 264–271.
38. Hong, X.-C.; Cheng, S.; Liu, J.; Dang, E.; Wang, J.-B.; Cheng, Y. The Physiological Restorative Role of Soundscape in Different Forest Structures. *Forests* **2022**, *13*, 1920. [CrossRef]
39. Koprowska, K.; Łaszkiewicz, E.; Kronenberg, J.; Marcińczak, S. Subjective perception of noise exposure in relation to urban green space availability. *Urban For. Urban Green.* **2018**, *31*, 93–102. [CrossRef]
40. Deng, J.Y.; He, Y.; Dai, M. Evaluation of the outdoor thermal environment for three typical urban forms in Nanjing, China. *Build. Environ.* **2023**, *238*, 110358. [CrossRef]
41. He, B.J.; Ding, L.; Prasad, D. Urban ventilation and its potential for local warming mitigation: A field experiment in an open low-rise gridiron precinct. *Sustain. Cities Soc.* **2020**, *55*, 102028. [CrossRef]

42. Hong, X.C.; Wang, G.Y.; Liu, J.; Dang, E. Perceived Loudness Sensitivity Influenced by Brightness in Urban Forests: A Comparison When Eyes Were Opened and Closed. *Forests* **2020**, *11*, 1242. [CrossRef]
43. Zhao, Z.Q.; He, B.J.; Li, L.G.; Wang, H.B.; Darko, A. Profile and concentric zonal analysis of relationships between land use/land cover and land surface temperature: Case study of Shenyang, China. *Energy Build.* **2017**, *155*, 282–295. [CrossRef]
44. Jo, H.I.; Jeon, J.Y. Overall environmental assessment with soundscape and landscape indices in urban parks. In Proceedings of the 13th ICBEN Congress on Noise as a Public Health Problem, Stockholm, Sweden, 14–17 June 2021.
45. Liu, X.; He, J.; Xiong, K.; Liu, S.; He, B.J. Identification of factors affecting public willingness to pay for heat mitigation and adaptation: Evidence from Guangzhou, China. *Urban Clim.* **2023**, *48*, 101405. [CrossRef]
46. Yang, J.; Sun, J.; Ge, Q.; Li, X. Assessing the impacts of urbanization-associated green space on urban land surface temperature: A case study of Dalian, China. *Urban For. Urban Green.* **2017**, *22*, 1–10. [CrossRef]
47. Saher, R.; Stephen, H.; Ahmad, S. Effect of land use change on summertime surface temperature, albedo, and evapotranspiration in Las Vegas Valley. *Urban Clim.* **2021**, *39*, 100966. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

forests

MDPI

*Article*

# Combined Effects of the Thermal-Acoustic Environment on Subjective Evaluations in Urban Park Based on Sensory-Walking

**Ye Chen, Fan Liu, Xinya Lin, Jing Liu, Ziyi Chen, Kailong Shi, Junyi Li and Jianwen Dong ***

College of Landscape Architecture and Art, Fujian Agriculture and Forestry University, 15 Shangxiadian Rd., Fuzhou 350000, China; 2191775001@fafu.edu.cn (Y.C.); 2221775007@fafu.edu.cn (F.L.); 1201775025@fafu.edu.cn (X.L.); 1211775034@fafu.edu.cn (J.L.); 3211726008@fafu.edu.cn (Z.C.); 3211775025@fafu.edu.cn (K.S.); 3191726026@fafu.edu.cn (J.L.)
* Correspondence: fjdjw@fafu.edn.cn

**Abstract:** Studying the impact of various factors on environmental perception is crucial because humans live in an environment where these factors interact and blend. The thermal-acoustic environment is the major factor that affects the overall perception of urban parks. This study focuses on urban parks in the subtropical region, with Xihu Park in Fuzhou, China, as the research area. Through measurements and questionnaires, this study explores the effects of the thermal-acoustic environment in urban parks on subjective evaluation (thermal assessment, acoustic assessment, and overall environmental assessment). The results reveal that: (1) a higher temperature significantly increases the sensation of heat and lowers thermal comfort, heat acceptance, and overall thermal environment evaluation scores. The type of sound source has a significant positive impact on thermal assessment, and the higher the ranking of the sound source type, the greater its positive impact on thermal assessment. (2) Regarding acoustic evaluation, higher sound pressure level is associated with more negative subjective ratings of loudness, harshness, intensity, and excitement. In contrast, positive sound sources can enhance comfort, preference, disorder, coordination, and overall soundscape evaluation. Additionally, temperature increases tend to result in more negative harshness, intensity, and coordination ratings. The interaction between temperature and sound pressure level also significantly affects subjective loudness, harshness, and intensity. (3) Overall environmental evaluation is also affected by temperature, with increasing temperatures leading to decreased comfort and satisfaction while increasing irritation. High sound pressure environments result in worse overall irritation ratings, while positive sound sources can significantly enhance overall comfort, irritation, and satisfaction ratings. Furthermore, the interaction between temperature and sound pressure level significantly impacts overall irritation and satisfaction ratings. These findings are significant for managing and improving the park's thermal environment and soundscape, providing a practical framework for landscape architects.

**Keywords:** urban park; combined effects; temperature; acoustic; subjective evaluations; Fuzhou city; soundscape

**Citation:** Chen, Y.; Liu, F.; Lin, X.; Liu, J.; Chen, Z.; Shi, K.; Li, J.; Dong, J. Combined Effects of the Thermal-Acoustic Environment on Subjective Evaluations in Urban Park Based on Sensory-Walking. *Forests* **2023**, *14*, 1161. https://doi.org/10.3390/f14061161

Academic Editors: Chi Yung Jim and Timothy A. Martin

Received: 8 April 2023
Revised: 24 May 2023
Accepted: 3 June 2023
Published: 5 June 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

With the acceleration of the urbanization process as a phenomenon of the 21st century, a variety of environmental problems have arisen, including water scarcity [1,2], industrial and community waste [3], soil pollution [4], population density increase [5], noise discomfort [6,7], and climate change [8,9]. In this regard, outdoor noise exposure impacts human health, such as hearing loss, sleep disruption, and cardiovascular and mental health disorders [10–12]. On the other hand, the direct impact of climate change on people's quality of life and the emergence of a phenomenon called the Urban Heat Island (UHI) have led to thermal discomfort in urban space [13–15]. Therefore, urban parks are considered an

integral part of the complex urban ecosystem network, providing various advantages for city residents [16]. Open green spaces in urban parks can improve physical and mental health by reducing exposure to air and noise pollution and extreme heat and providing psychological relaxation and stress relief [17].

Despite extensive research on subjective evaluations linking human perception and comfort levels to specific environmental factors in various urban parks, the study of comprehensive influences of different factors remains insufficient [18–20]. As people engage in recreational activities within a multi-faceted, interactive park environment, studying the impact of individual factors on human perception [21] or comfort [22] level fails to represent their genuine environmental evaluations fully. Therefore, it is necessary to investigate the effects of multiple factors on assessing urban park environments.

The soundscape refers to the combination of all sound elements within a specific area, which reflects the cultural, social, and ecological characteristics of that area and can impact individuals' emotional behavior and health status, soundscape should be considered a natural resource that is worthy of management and protection, and therefore suitable measures must be taken [23–26]. Kang (2023) discussed soundscape research's current state and development and explored a framework for using soundscape methodology in urban sound design and planning processes [27]. Francesco, A (2023) integrated smart growth concepts, urban design, and soundscape in a groundbreaking manner. He emphasizes the potential of the soundscape to effectively tackle common noise issues in residential areas [28]. Extensive research has been conducted by scholars from both domestic and international fields on the impact of multiple factors on environmental evaluation [29], particularly on soundscape evaluation [30]. Studies have shown that human visual perception affects auditory perception and the coordination and coherence between sound and image influence preference [31].

Furthermore, sound can serve as supplementary information to visual stimulation [32]. This highlights the crucial role of the relationship between audio and visual elements in creating a comprehensive and effective multimedia experience. With the increase in urban scenery, auditory experiences have become even more complicated. However, research has found that integrating and coordinating auditory and visual elements can enhance aesthetic preferences. Matching soundscapes with visual landscapes can produce a broader and more cohesive sensory experience [33].

Meanwhile, past research has indicated that the thermal environment significantly impacts soundscape evaluation. Factors such as temperature, humidity, lighting, wind, and changes in visual and auditory elements may also affect soundscape assessment, with environmental factors being the most prominent [34,35]. Other scholars have also researched the influence of smell on auditory perception. Through virtual reality experiments, it was discovered that smell could affect the evaluation of road traffic environments, demonstrating its potential to regulate noise and visual landscape perception in specific contexts [36]. Ba and Kang (2019) demonstrated that the presence of smell has almost no impact on the evaluation of bird songs or low-volume sounds, but under certain conditions, a higher concentration of smell leads to more positive evaluations [37]. Several scholars have researched the combined impact of thermal and acoustic environments on physical comfort regarding the comprehensive influence of thermal acoustics. Zhou et al. (2021) discovered that exposure to temperature, noise, and vibration can significantly affect the overall satisfaction of study participants [38].

Regarding the impact of a thermal, acoustic environment on human comfort, Pellerin Nicolas et al. (2003) found that although the combined effect of noise and temperature does not affect physiological data, their research results indicate that noise may alter thermal comfort under warm conditions [39]. Moreover, various factors, such as temperature and noise, have been studied by scholars for their impact on human comfort. Wu et al. discovered that temperature has a significant effect on most subjective and objective parameters, while illumination has a weaker impact. Temperature and illumination are the two primary environmental factors that affect comfort. Furthermore, research has found that

the interaction between color temperature and the temperature has a significant effect on several evaluation parameters [40]. Li et al. (2012) suggest that both temperature and noise satisfaction hold veto power over overall indoor environmental satisfaction, significantly outweighing the importance of lighting satisfaction significantly [41].

A summary of previous research methods indicates that researchers often opt for laboratory or controlled indoor environments as research settings to explore the impact of thermal and acoustic environments on human subjective evaluations. As a result of the relatively stable thermal environment and the ability to effectively control various factors in these venues, currently, there is a lack of research on the subjective evaluation of humans under different thermal-acoustic conditions in real park environments. Urban parks are a significant component of urban construction and an important part of urban ecological systems and city landscapes. They provide a place for urban residents to meet their leisure needs, relax, exercise, socialise, and hold various cultural activities. Therefore, they were chosen as the outdoor research site for this study. Generally, urban parks are located around urban arterials and are often affected by traffic noise at their boundaries.

Additionally, the diverse spatial types within the park and the significant differences in thermal environments influence visitors' environmental evaluations. Therefore, considering factors such as the number of visitors, thermal acoustic environment conditions, and improvement needs, urban parks are conducive to investigating tourists' subjective evaluations under different thermal and acoustic conditions. Finally, it is worth noting that although the activity status of urban park visitors impacts environmental evaluations, in this study, all participants were required to stand or sit [42] when answering the questionnaire. Thus, the instantaneous thermal, acoustic environment has a more significant impact on subjective evaluations.

Considering the limitations of previous research and the necessity of improving the thermal and acoustic environment in urban parks, the present study aims to explore the following aspects: (1) Subjective evaluation of different spaces in the park's environment will be conducted through sensory walks and questionnaires. (2) Objective data such as temperature, global temperature, relative humidity, average wind speed (Va), equivalent continuous sound level (LAeq), as well as dominant sound sources will be collected through monitoring devices to comprehensively understand the park's actual environment and differences in the thermal-acoustic of different areas. This will lay the foundation for the analysis section. (3) Furthermore, this study aims to explore the impact of thermal acoustic on the subjective evaluation of the park. The questionnaires will be analysed to investigate how thermal acoustics affect sound and thermal evaluations as well as overall environmental evaluations of the park. Through these explorations, we hope to provide more scientific suggestions for improving the urban park's thermal acoustics environment.

## 2. Materials and Methods

### *2.1. Study Site Overview*

This research was conducted in Fuzhou, a typical city in the humid subtropical region of China. Fuzhou has a pleasant and humid climate with evergreen seasons, abundant sunshine, rainfall, and a short winter and long summer. The frost-free period reaches up to 326 days annually. The average annual sunshine hours are between 1700 and 1980, and the average annual rainfall is between 900 and 2100 mm. The average annual temperature is 20–25 °C, with the coldest month being December and an average temperature of 6–10 °C, and the hottest month being July and August with an average temperature of 33–37 °C. Extreme temperatures range from 2.5 to 42.3 °C annually. The average relative humidity is about 77%, and the city often experiences the urban heat island effect due to its basin topography, where the temperature can reach over 36 °C at noon in summer. The dominant wind direction is northeast, with south wind prevailing in summer [43]. The research site was selected based on whether it had common sound sources and thermal environments in urban parks. To investigate the effect of the thermal, acoustic environment on subjective

evaluations of urban parks, considering factors such as the park area and its accessibility, the Xihu Park, located in the city center, was finally chosen.

Xihu Park is located in the northwest part of Gulou District, Fuzhou City, and is situated at the city's center, adjacent to residential, commercial, and office areas in the city center. It's only 700 m away from the main transportation artery Yangqiao East Road and can be reached by a 10-min walk. With a history of more than 1700 years, it is the most well-preserved classical garden in Fuzhou, and it is renowned as the "Pearl of Fujian Gardens", ranking among the top 36 West Lakes in the country. Currently, it covers an area of 42.51 hectares, with a land area of 12.21 hectares and a water area of 30.3 hectares. The vegetation composition in Xihu Park is complex, dominated by forests, grasslands, shrub beds and flower gardens. The forest area is relatively large, consisting primarily of deciduous and mixed coniferous forests. The deciduous broad-leaved forest in the Huxin Mountain is the most typical, characterized by dominant tree species such as nanmu, camphor, banyan, and paulownia, forming a natural, primitive, and spectacular ecosystem. The grasslands consist of common lawn grass and some wildflowers, while the shrubs comprise flower bushes and climbing plants. The rich and diverse vegetation composition of Xihu Park is functionally complete, providing an ideal place for urban ecological construction and for citizens to relax, exercise and enjoy their leisure time [44].

There are a total of 12 sample sites in Xihu Park. The panoramic view of these sites can be seen in the accompanying Figure 1. In addition, on a representative date of the summer season (5 September), a subjective questionnaire survey will be conducted to monitor the thermal and acoustic environment.

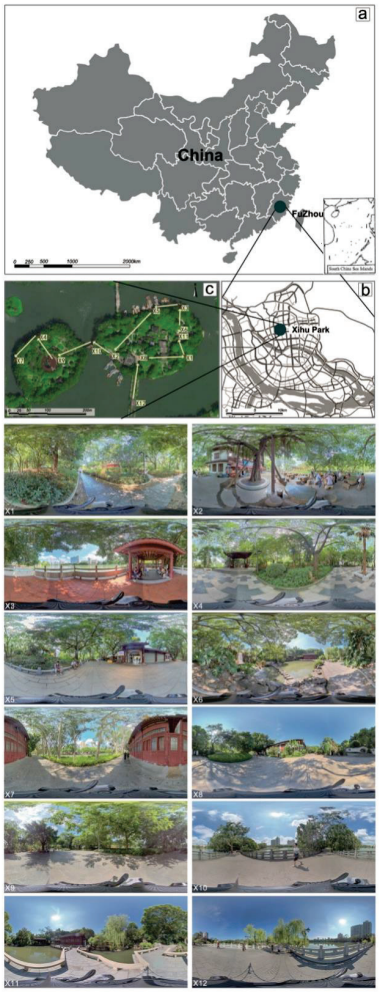



**Figure 1.** (**a**) Location of Fuzhou city in China map; (**b**) Xihu Park in Fuzhou city; (**c**) 12 sample sites within Xihu Park.

### 2.2. Procedures

Regarding the evaluation indicators for the acoustic environment, due to the discontinuity of sound in the park area, this study has opted for the LAeq (weighted equivalent continuous sound level) as the primary evaluation indicator. Moreover, given the variety of sound types in the park, the primary ranking of the dominant sound source type based on the First Impression Sound Source (TP) will be selected as the evaluation indicator through voting. The index ranks in ascending order through positive and negative effects on the sound source, presented as categorical variables [45–49]. As for the evaluation indicators for the thermal environment, due to the instability of the outdoor thermal environment, this study has selected the Universal Thermal Climate Index (UTCI) to evaluate the thermal physiological effects of the thermal environment. The UTCI represents the equivalent environmental temperature of the reference environment and provides the same physiological response as the reference person in the actual environment. This indicator integrates subjective factors and objective environmental parameters while considering the human body's thermal adaptability [50–53]. The UTCI value is derived from the thermal environmental parameters gathered in the questionnaire survey. Once data on radiation temperature, air temperature, relative humidity, wind speed, and global temperature are prepared, the UTCI can be calculated using either the BioKlima2.6 software or the Fortran program available on the official website (http://www.utci.org, accessed on 1 December 2022). The deviation of UTCI from air temperature is determined by actual air temperature ($T_a$), mean radiant temperature ($T_{mrt}$), wind speed ($V_a$), and relative humidity (Rh). This can be expressed by a formula [54].

$$UTCI = T_a + Offset\ (T_a, T_{mrt}, V_a, Rh) = f\ (T_a, T_{mrt}, V_a, Rh) \quad (1)$$

In the formula, $T_a$ represents the temperature of a 2 m air column, $V_a$ represents the wind speed of 10 ms, $P_a$ represents the relative humidity, and $T_{mrt}$ represents the average radiative temperature.

### 2.3. Questionnaire Survey and Analysis

Sensory Walk [55] was primarily used as the main research method in this experiment, involving various urban park spatial environments throughout the entire walking route to explore the pattern of acoustic-thermal interaction under different spatial environment conditions. The core of the Sensory Walk is to listen and feel the entire environment. After walking along the designated route and listening to the surroundings, a 5-point Likert scale was adopted to evaluate the thermal, acoustic, and overall environment subjectively. As shown in Tables 1–3, the participants were evaluated based on their subjective loudness vote (SLV), acoustic comfort vote (ACV), acoustic coordination vote (ACoV) [56], acoustic preference vote (APV) [57], acoustic harshness vote (AHV), acoustic pleasure vote (APlV), acoustic familiarity vote (AFV), acoustic intensity vote (AIV), acoustic excitability vote (AEV), acoustic disorder vote (ADV) [58], overall acoustic vote (OAV) [59], thermal sensation vote (TSV), thermal comfort vote (TCV), thermal acceptance vote (TAV), overall thermal vote (OTV) [60], overall comfort vote (OCV), overall annoyance vote (OAnV), and overall satisfaction vote (OSV) [61]. The data were collected to assess various aspects of the acoustic and thermal environment, including subjective evaluation of sound properties, temperature perception, and overall comfort, annoyance, and satisfaction levels. The questionnaire survey as Appendix A.

**Table 1.** Subjective evaluations of the questionnaire surveys (TSV, TCV, TAV, OTV).

| Scores | Thermal Sensation | Thermal Comfort | Thermal Acceptance | Overall Thermal |
|---|---|---|---|---|
| 1 | Cold | Uncomfortable | unacceptable | Bad |
| 2 | cool | Slightly Uncomfortable | Slightly unacceptable | Slightly bad |
| 3 | Neutral | Neutral | Neutral | Neutral |
| 4 | warm | Slightly Comfortable | Slightly acceptable | Slightly good |
| 5 | Hot | Comfortable | acceptable | Good |

**Table 2.** Subjective evaluations of the questionnaire surveys (SLV, ACV, APV, AHV, APlV, AFV, AIV, AEV, ADV, ACoV, OAV).

| Scores | Subjective Loudness | Acoustic Comfort | Acoustic Preference | Acoustic Harshness | Acoustic Pleasure | Acoustic Familiarity | Acoustic Intensity | Acoustic Excitability | Acoustic Disorder | Acoustic Coordination | Overall Acoustic |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Quiet | Uncomfortable | Unlike | Gentle | Unhappy | Strange | Weak | Calm | Monotonous | Incoordinate | Bad |
| 2 | Slightly quiet | Slightly Uncomfortable | Slightly unlike | Slightly Gentle | Slightly Unhappy | Slightly Strange | Slightly weak | Slightly Calm | Slightly monotonous | Slightly incoordinate | Slightly bad |
| 3 | Neutral | Neutral | Neutral | Neutral | Neutral | Neutral | Neutral | Neutral | Neutral | Neutral | Neutral |
| 4 | Slightly Loud | Slightly Comfortable | Slightly like | Slightly harsh | Slightly happy | Slightly familiar | Slightly strong | Slightly excited | Slightly disordered | Slightly coordinate | Slightly good |
| 5 | Loud | Comfortable | Like | Harsh | Happy | Familiar | Strong | Excited | Disordered | Coordinate | Good |

**Table 3.** Subjective evaluations of the questionnaire surveys (OCV, OAnV, OSV).

| Scores | Overall Comfort | Overall Annoyance | Overall Satisfaction |
|---|---|---|---|
| 1 | Uncomfortable | Peaceful | Bad |
| 2 | Slightly Uncomfortable | Slightly Peaceful | Slightly bad |
| 3 | Neutral | Neutral | Neutral |
| 4 | Slightly Comfortable | Slightly annoying | Slightly good |
| 5 | Comfortable | annoying | Good |

### *2.4. Measurements*

The Kestrel 5500 portable weather station was utilized to record temperature, relative humidity, and wind speed. The BES-01 temperature logger was chosen to measure global temperature with a diameter of 0.08m and a surface material scattering coefficient of 0.95. Additionally, the BES-02 temperature and humidity logger was employed to measure air temperature and humidity. The BSWA801 noise and vibration analyzer was utilized to record sound pressure levels in the park environment. All instruments were calibrated before operation. The temperature logger was placed inside a radiation shield to avoid interference from solar radiation and wind.

Meanwhile, the microphone of the analyzer was placed inside a windscreen for more accurate recordings. The instruments were set up according to ISO 772628 [62] and securely mounted on a tripod approximately 1.2 m above ground level. Instrument specifications are detailed in Table 4.

**Table 4.** The characteristics of the instruments.

| Type | Range | Precision |
|---|---|---|
| Kestrel 5500 weather station | 0.4~40 m/s | ±0.1 m/s |
| BES-01 temperature recorder | −30 °C~50 °C | ±0.5 °C |
| BES-02 temperature And humidity recorder | −30 °C~50 °C<br>0%~99% RH | ±0.5 °C<br>±3% RH |
| BSWA801 noise vibration analyser | 19 dB(A)~137 dB(A) | <0.7dB (A) |

### 2.5. Subjects

The current study involved 30 subjects, from whom 360 valid questionnaires were collected. All individuals were approached in a park, informed about the purpose of the survey, and voluntarily agreed to participate. Of the subjects, 56.67% were male, and 43.33% were female, with 80% falling between 18 and 30. Moreover, 83.33% (25 individuals) reported residing in Fuzhou for over one year. The subjects had a metabolic equivalent of 1.2 met, and their average clothing insulation was 0.48 clo.

### 2.6. Experimental Process

Firstly, the study's leader provided face-to-face training for all 30 subjects, explaining the basic concept of soundscape, the significance of the experiment, and how to fill out the questionnaire, including the explanation of soundscape questions and answers. Secondly, the leader led the participants through a sensory walk experiment in 12 different areas. The participants were divided into three groups, each supervised by a leader. To avoid overcrowding, there was a 10m distance between each group, and the leading participant controlled the distance [63].

During the sensory-walking experiment, the participants were not allowed to speak, eat or drink to reduce human noise. Finally, they walked through each designated sensory walking area along a specified route. The group stopped at each site for five minutes, standing or sitting while carefully listening to sound elements and feeling the thermal environment, then filled out a questionnaire online. The experimental process is shown in Figure 2. The primary leader was also responsible for using equipment to collect data, including temperature, global temperature, humidity, wind speed, and the LAeq (a weighted equivalent continuous sound level), for a continuous period of 5 min [64].

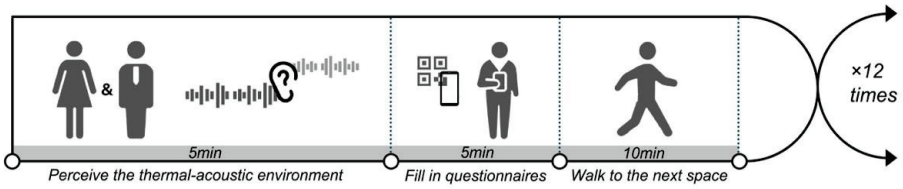



**Figure 2.** Experimental process.

### 2.7. Analysis Method

The experimental results were free of missing values, and any outliers were eliminated or replaced to ensure the accuracy and reliability of the data. Following data collection and organization, objective parameters were standardized to calculate each variable's mean and standard deviation.

In both production activities and scientific experiments, the generation of results is often influenced by multiple factors with varying degrees of impact. ANOVA, a statistical method, infers whether one or more factors have a significant impact on the experimental results when they change at different levels. The study utilized the SPSS27.0 statistical analysis software to analyze subjective perception data of the environment. The variance analysis method (ANOVA) was employed to explore the differences in the impact of thermal-acoustic elements on subjective perception, and the Mauchly sphericity test was conducted. When the results did not satisfy the sphericity assumption ($p < 0.05$), a correction was needed. The Greenhouse-Geisser correction was chosen when Epsilon < 0.75, while the Huynh-Feldt correction was selected in other situations [65]. The final experimental data passed validation before analysis.

## 3. Results

### 3.1. Basic Environmental Conditions

The researchers conducted a sensory walk experiment in 12 different areas under the guidance of local experts and research teams, following a pre-established plan. Table 5 illustrates the basic thermal-acoustic data acquired through equipment in the 12 areas.

**Table 5.** Sample thermal-acoustic environment situation.

| Plot | Ta (°C) | Ts (°C) | Humidity (%) | Va (m/s) | UTCI (°C) | LAeq (dB) | Source Type |
|---|---|---|---|---|---|---|---|
| 1 | 30.30 | 30.50 | 57.50 | 0.00 | 31.35 | 53.90 | 2 (bird song) |
| 2 | 31.10 | 31.20 | 54.40 | 0.40 | 32.16 | 64.60 | 5 (conversations) |
| 3 | 31.40 | 31.70 | 55.60 | 0.00 | 32.50 | 58.60 | 5 (conversations) |
| 4 | 31.60 | 31.80 | 70.10 | 0.20 | 34.68 | 52.90 | 3 (rustling leaves) |
| 5 | 32.00 | 33.10 | 68.20 | 0.00 | 35.03 | 61.10 | 4 (broadcasting music) |
| 6 | 31.90 | 32.80 | 73.10 | 0.10 | 35.77 | 71.50 | 1 (water) |
| 7 | 32.30 | 33.50 | 68.20 | 0.30 | 35.89 | 51.10 | 2 (bird song) |
| 8 | 32.60 | 33.50 | 68.10 | 0.30 | 36.16 | 59.40 | 4 (radio music) |
| 9 | 32.80 | 34.60 | 65.20 | 0.10 | 36.19 | 54.20 | 2 (bird song) |
| 10 | 33.80 | 35.50 | 62.60 | 0.80 | 37.56 | 59.50 | 4 (broadcasting music) |
| 11 | 34.10 | 36.20 | 65.70 | 0.10 | 38.26 | 63.50 | 1 (water) |
| 12 | 34.80 | 36.80 | 61.00 | 0.60 | 38.92 | 77.80 | 6 (Construction noise) |

### *3.2. Comprehensive Impact of Thermal Acoustic Environment on Thermal Assessment*

The impact of the thermal and acoustic environment on thermal assessment includes the effects on TSV, TCV, TAV, and OTV. Table 6 demonstrates the significance of the indicators under main effects and interaction effects (TSV, TCV, TAV, and OTV). The analysis of variance (ANOVA) indicates that the main effects of UTCI significantly influence TSV ($p < 0.01$), TCV ($p < 0.05$), TAV ($p < 0.05$), and OTV ($p < 0.1$). On the other hand, the interaction effect between LAeqUTCI and LAeq has no significant impact on all thermal assessments ($p > 0.1$), while the main effects of TP significantly influence TSV, TCV, and OTV ($p < 0.01$).

**Table 6.** The significance of the indicators under the main effect and interaction (TSV, TCV, TAV, and OTV).

| Subjective Evaluation | UTCI | LAeq | UTCI × LAeq | TP |
|---|---|---|---|---|
| TSV | **0.003** | 0.196 | 0.12 | **0** |
| TCV | **0.016** | 0.298 | 0.221 | **0.001** |
| TAV | **0.039** | 0.219 | 0.155 | 0.225 |
| OTV | **0.059** | 0.611 | 0.458 | **0.007** |

Note: Bold indicates significant correlation within 0.1.

Figure 3 illustrates the TSV values of 12 sample sites. Concerning the impact of the thermal environment on TSV, there is a significant increasing trend in TSV as UTCI increases. When UTCI is lower than 36, TSV is concentrated in the moderate range, while the deviation of TSV is greater when UTCI is above 36. As for the influence of noise environment on TSV, LAeq has little effect on TSV as a whole. However, when UTCI is below 34 or above 37, TP can affect TSV and the degree of deviation increases.

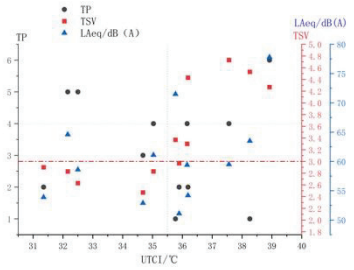



**Figure 3.** The values of TSV under different conditions of the thermal-acoustic environment.

Figure 4 demonstrates the TCV values of the 12 sample sites. Regarding the impact of the thermal environment on TCV, there is an obvious decreasing trend in TCV as UTCI increases. When UTCI is around or below 35.5, TCV is relatively comfortable, and discomfort rises when UTCI exceeds 36. As for the impact of noise environment on TCV, LAeq has little effect on TCV as a whole. Nevertheless, positive TP can increase TCV when UTCI is below 36.

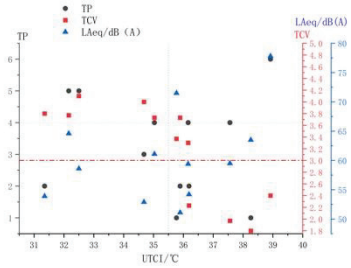



**Figure 4.** The values of TCV under different conditions of the thermal-acoustic environment.

Figure 5 illustrates the TAV values of 12 sample sites. Regarding the impact of the thermal environment on TAV, there is a significant decrease in TAV with the increase of UTCI. When the UTCI value is below 36, the TAV score is higher, while the degree of thermal comfort significantly reduces when the UTCI value exceeds 36. As for the impact of the acoustic environment on TAV, LAeq and TP have no significant influence on TAV as a whole.

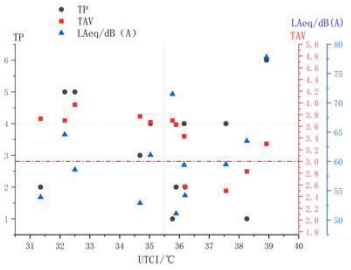



**Figure 5.** The values of TAV under different conditions of the thermal-acoustic environment.

Figure 6 displays the OTV values of 12 sample sites. Concerning the impact of the thermal environment on OTV, there is a significant decrease in OTV with the increase of UTCI. When the UTCI value is below 36, the OTV score is higher than neutral, but it falls below neutral when the UTCI value exceeds 36. As for the impact of the acoustic environment on OTV, LAeq has no significant influence on OTV as a whole. However, when UTCI is around 35.5, the positive TP can increase the OTV score.

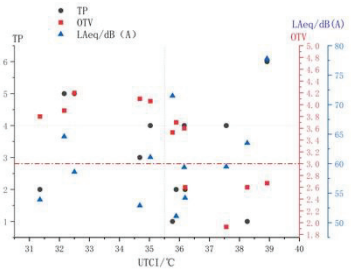



**Figure 6.** The values of OTV under different conditions of the thermal-acoustic environment.

### *3.3. Comprehensive Influence of Thermal Acoustic Environment on Acoustic Assessment*

To ensure the consistency of the results and avoid misleading situations, the inversion of the rating procedure is adopted before statistical analysis, with the parameters of ACV, APV, AFV, and OAV being flipped [66]. The impact of the thermal, acoustic environment on acoustic assessment includes its effect on 11 indicators, namely, SLV, ACV, APVA, HVA, PlVAF, VAIV, AEV, ADV, ACoV and OAV. Table 7 demonstrates the significance of the main effects and interactions of these indicators. Variance analysis reveals that UTCI has a significant main effect on AHV ($p < 0.1$), AIV ($p < 0.01$) and AEV ($p < 0.1$). LAeq has a significant main effect on SLV ($p < 0.01$), AHV ($p < 0.01$), AIV ($p < 0.01$) and AEV ($p < 0.05$). The interaction effect of UTCI and LAeq has a significant impact on SLV ($p < 0.05$), AHV

($p < 0.05$), AIV ($p < 0.01$), and AEV ($p < 0.05$). Meanwhile, TP has a significant main effect on ACV, APVA, DVO and OAV ($p < 0.1$).

**Table 7.** The significance of the indicators under the main effect and interaction (SLV, ACV, APVA, HVA, PlVAF, VAIV, AEV, ADV, ACoV and OAV).

| Subjective Evaluation | UTCI | LAeq | UTCI × LAeq | TP |
|---|---|---|---|---|
| SLV | 0.133 | **0.007** | **0.034** | 0.12 |
| ACV | 0.209 | 0.129 | 0.133 | **0.001** |
| APV | 0.699 | 0.474 | 0.513 | **0.019** |
| AHV | **0.086** | **0.007** | **0.027** | 0.418 |
| APlV | 0.577 | 0.394 | 0.441 | 0.26 |
| AFV | 0.969 | 0.858 | 0.887 | 0.581 |
| AIV | **0.006** | **0** | **0.001** | 0.222 |
| AEV | **0.058** | **0.014** | **0.034** | 0.137 |
| ADV | 0.518 | 0.417 | 0.333 | **0.002** |
| ACoV | **0.093** | 0.135 | 0.147 | **0.042** |
| OAV | 0.724 | 0.748 | 0.739 | **0.082** |

Note: Bold indicates significant correlation within 0.1.

Figure 7 illustrates the SLV values of 12 different sample sites, showing a significant increase in SLV with an increasing LAeq due to the influence of noise. When the LAeq exceeds 53 dB(A), SLV values are consistently higher than the neutral level. In terms of the impact of the thermal environment on SLV, the UTCI has no significant effect on the overall SLV.

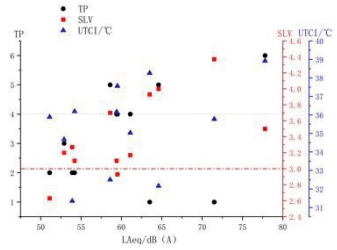



**Figure 7.** The values of SLV under different conditions of the thermal-acoustic environment.

Figure 8 displays the ACV values of the same 12 sample sites, indicating that the ACV value decreases to some extent when the TP is below four due to the influence of noise. Regarding the impact of the thermal environment on ACV, the UTCI has no significant effect on the overall ACV.

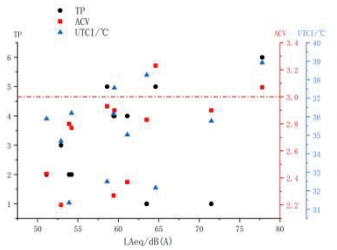



**Figure 8.** The values of ACV under different conditions of the thermal-acoustic environment.

Figure 9 illustrates the APV values at 12 different sites. Regarding the impact of a sound environment on APV, values tend to decrease when TP is below 4. As for the effect of the thermal environment on APV, UTCI does not have a significant overall impact.

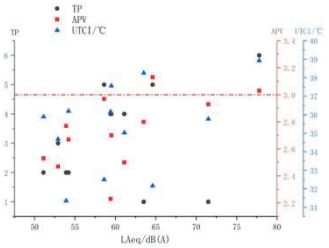



**Figure 9.** The values of APV under different conditions of the thermal-acoustic environment.

Figure 10 reveals the AHV values at the same 12 sites. Regarding the influence of a sound environment on AHV, values tend to increase when TP is below 4. In terms of the effect of the thermal environment on AHV, UTCI leads to an increase in deviation.

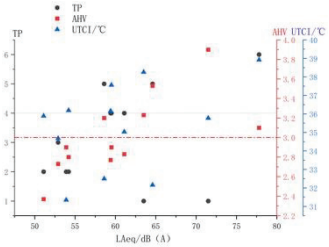



**Figure 10.** The values of AHV under different conditions of the thermal-acoustic environment.

Figure 11 displays the APlV values at the same 12 sites. Regarding the impact of a sound environment on APlV, SLV significantly increases as LAeq increases. When LAeq is over 53 dB(A), SLV exceeds the neutral level. As for the effect of the thermal environment on APlV, UTCI does not have a significant overall impact.

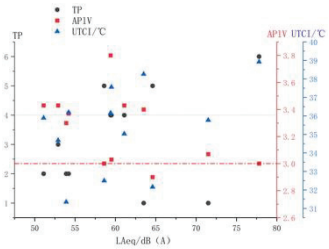



**Figure 11.** The values of APlV under different conditions of the thermal-acoustic environment.

Figure 12 exhibits the AFV values at the same 12 sites. Again, neither sound nor thermal environment has a significant overall impact on AFV.

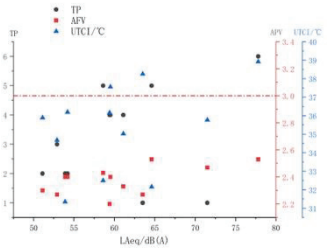



**Figure 12.** The values of AFV under different conditions of the thermal-acoustic environment.

Figure 13 illustrates the AIV values of 12 plots. Regarding the impact of the acoustic environment on AIV, AIV significantly increases with the increase of LAeq. Concerning the impact of the thermal environment on AIV, as the UTCI grows, AIV's deviation becomes larger.

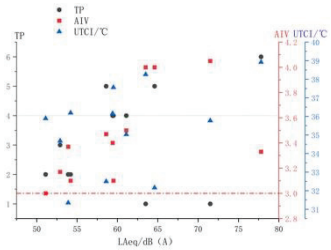



**Figure 13.** The values of AIV under different conditions of the thermal-acoustic environment.

Figure 14 depicts the AEV values of 12 plots. Concerning the impact of the acoustic environment on AEV, SLV significantly increases with the increase of LAeq. Regarding the impact of the thermal environment on AEV, as the UTCI grows, AEV's deviation becomes larger.

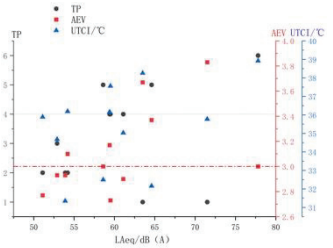



**Figure 14.** The values of AEV under different conditions of the thermal-acoustic environment.

Figure 15 shows the ADV values of 12 plots. Regarding the impact of the acoustic environment on ADV, LAeq has little effect. However, positive TP reduces ADV. Concerning the impact of the thermal environment on ADV, UTCI has no significant impact on the overall ADV.

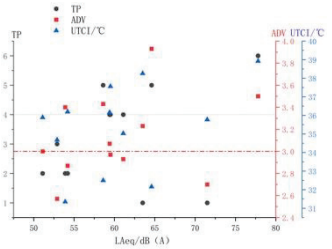



**Figure 15.** The values of ADV under different conditions of the thermal-acoustic environment.

Figure 16 displays the ACoV values for 12 plots. Regarding the impact of the acoustic environment on ACoV, LAeq has a negligible effect. However, positive TP reduces ACoV. Regarding the influence of the thermal environment on ACoV, an increase in UTCI results in higher ACoV deviations.

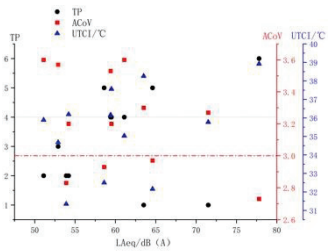



**Figure 16.** The values of ACoV under different conditions of the thermal-acoustic environment.

Figure 17 exhibits the OAV values for the same 12 plots. In terms of the effect of the acoustic environment on OAV, LAeq has no significant effect. Nevertheless, positive TP

increased OAV. Regarding the effect of the thermal environment on OAV, UTCI has little overall impact on OAV.

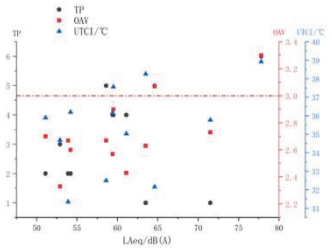



**Figure 17.** The values of OAV under different conditions of the thermal-acoustic environment.

### *3.4. Comprehensive Influence of Thermal Acoustic Environment on the Overall Environmental Assessment*

To ensure consistency of the results and avoid misleading situations, the inversion of rating was implemented for OCV and OSV parameters. The impact of the thermal environment on overall environmental assessment includes three indicators: OCV, OAnV, and OSV. Table 8 presents the significance of these indicators under main effects and interaction effects (OCV, OAnV, OSV). The main effect of UTCI is significant on OCV ($p < 0.05$), OAnV ($p < 0.01$) and OSV ($p < 0.05$). The main impact of LAeq is significant on OAnV ($p < 0.05$). Moreover, the interaction effect of UTCI $\times$ LAeq is significant on OAnV ($p < 0.05$) and OSV ($p < 0.1$). Finally, TP significantly affects all three overall indicators ($p < 0.01$).

**Table 8.** The significance of the indicators under the main effect and interaction (OCV, OAnV and OSV).

| Subjective Evaluation | UTCI | LAeq | UTCI × LAeq | TP |
|---|---|---|---|---|
| OCV | **0.015** | 0.252 | 0.158 | **0** |
| OAnV | **0.004** | **0.026** | **0.018** | **0** |
| OSV | **0.02** | 0.11 | **0.086** | **0.003** |

Note: Bold indicates significant correlation within 0.1.

Figure 18 illustrates the OCV values under various thermal and acoustic conditions. Regarding the influence of the thermal environment on OCV, a higher UTCI value corresponds to an overall upward trend in OCV. This escalation in discomfort is evident. Regarding the impact of the acoustic environment on OCV, LAeq does not appear to have a significant effect on the overall OCV trend. However, when UTCI is less than 34 or greater than 37, TP impacts OCV, leading to a greater deviation. Moreover, when UTCI falls between 34 and 37, TP $\leq$ 4 tends to have a lower score for OCV.

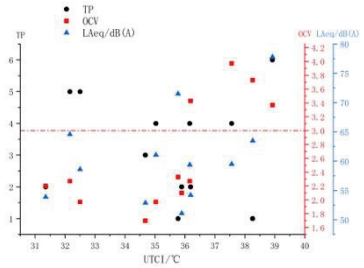



**Figure 18.** The values of OCV under different conditions of the thermal-acoustic environment.

Figure 19 presents the OAnV values under different thermal and acoustic conditions. Regarding the impact of the thermal environment on OAnV, as UTCI increases, OAnV demonstrates a significant upward trend. As for the influence of the acoustic environment on OAnV, higher values of LAeq and TP correspond to an overall increase in OAnV.

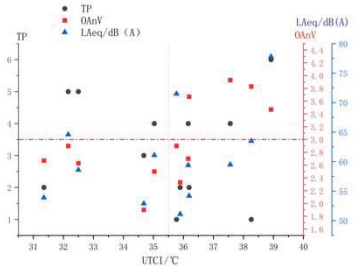



**Figure 19.** The values of OAnV under different conditions of the thermal-acoustic environment.

Figure 20 illustrates the OSV values under various thermal and acoustic environmental conditions. Although, regarding the impact of the thermal environment on OSV, there is a significant increase in OSV with an increase in UTCI, dissatisfaction with the manifestation is mounting. As for the impact of the acoustic environment on OSV, LAeq has little effect on OSV overall. However, when UTCI is less than 34 or greater than 37, TP can affect OSV and increase the deviation.

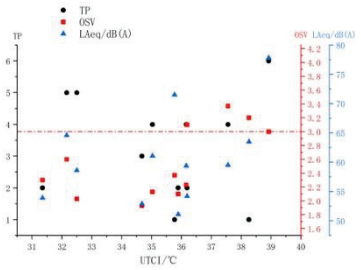



**Figure 20.** The values of OSV under different conditions of the thermal-acoustic environment.

## 4. Discussion

### *4.1. Interactions of the Thermal and Acoustic Environment*

Comfort is a significant aspect in the design of urban parks as it influences the behavior of visitors and the comfort of the park environment. Varying environmental factors, especially the thermal and acoustic environment, can improve the park space experience. This study investigates the impact of outdoor thermal and acoustic environment interactions and related indicators in 12 sample locations within a city park (Xihu Park, Fuzhou City).

(1) The findings of this study indicate that the thermal soundscape impacts the SLV, AHV, AIV, AEV evaluation of urban parks. The results indicate that people perceive higher soundscape quality in comfortable and cool environments during summer. The effect of LAeq on SLV, AHV, AIV, AEV depends on the different UTCI levels. When UTCI is below 36, SLV is concentrated near a neutral level. However, when UTCI exceeds 36, the diversity of SLV, AHV, AIV, AEV significantly increases. Moreover, research has found that positive sound sources, such as wind blowing through leaves, water, and birdsong, can significantly improve the overall rating of sound evaluation. This can be explained by the fact that this diverse range of sounds can make people's auditory systems more active and sensitive [67]. Additionally, these natural soundscape sources stem from comfortable environments. Extensive empirical research suggests that the auditory stimuli individuals receive within natural surroundings promote greater physical and mental health and comfort compared to indoor environments. From a physiological perspective, natural sounds lower stress hormone levels, improve sleep quality, strengthen immune system functionality, and positively impact emotions and cognition [68]. Hearing natural sounds also enhances feelings of comfort and tranquility [69]. Therefore, hearing natural sounds can make people feel more comfortable and peaceful. Increasing vegetation cover and regulating environmental temperature in urban parks can significantly enhance acoustic quality. The urban heat island effect and other modern urban environmental issues have worsened the acoustic environment in urban parks due to noise pollution

and temperature rise. Reasonable vegetation arrangements, such as vegetation and tree configuration, can reduce the thermal resistance caused by building surface pavement and other hard surfaces, thus helping to alleviate the impact of temperature rise. In addition, with economic development and technological advancements, the artificial intervention has become a new method for adjusting the thermal environment of urban parks, such as using artificial wetting and increasing reflectivity. Furthermore, natural elements, especially trees, in the urban park environment create a variety of positive soundscapes, making the environment more pleasant [70,71]. These research findings are similar to previous studies [35,70,72–74]. During hot seasons, low-level thermal sensation (environmental cooling), high-level thermal comfort, and positive sound sources significantly enhance soundscape quality. Therefore, these research results can provide important reference information for urban park planning and construction.

(2) In this study, it was found that although there was no interaction between UTCI and LAeq in terms of heat evaluation, positive sound sources (TP) had a significant impact on TSV, TCV and OTV. Within the inner area of the park, vegetation was able to shield noise pollution, resulting in a relatively stable range of LAeq readings. Thus, the type of sound source in the park became the primary factor affecting heat evaluation, a finding also supported by other researchers [70,75,76]. Particularly during hot seasons, positive sound sources were effective in reducing TSV and increasing TCV and OTV. The type of sound source plays a significant role in regulating the sensory experience of humans in urban park environments. One can argue that positive acoustic environments, with their gradual and soft sound characteristics, aid in relaxation, easing the pressure of the heat on the body, and enhancing a cool and pleasurable feeling, ultimately improving the evaluation of thermal comfort and overall thermal environment. For instance, in an outdoor recreational area, the soothing and tranquil natural sounds, such as birds chirping, cicadas, or rustling leaves, enable people to withstand the discomfort of heat waves, thereby improving thermal comfort and overall evaluation of the thermal environment. Additionally, in urban park environments, it is vital to consider the ratio of acoustic landscapes to buildings, among other factors, to achieve the gradual variation of sound and ensure smooth sound transmission throughout the park [77]. This highlights the need to control and manage sound sources in the park's inner area to reduce visitor perceptions of heat during hot seasons. Furthermore, with increasing urbanization, noise pollution in urban parks is expected to worsen. Thus, improving the acoustic environment within parks will become an important task for park management in the future.

(3) We conducted an analysis of the overall environmental assessment, focusing on the interaction between UTCI and LAeq, and discovered a significant positive correlation between this interaction and OAnV and OSV. Specifically, as the deviation from the neutral temperature sound level increased, the overall annoyance votes also increased. This result is consistent with previous studies [75,78], indicating that in parks, the overall sense of annoyance and satisfaction of the human body are simultaneously affected by temperature and sound pressure. This is mainly because the human body is a highly sensitive biological organism, and various factors in the environment, such as sound, light, smell, and temperature, can stimulate the human nervous system and body. In a park, temperature and sound pressure changes can cause varying degrees of physiological and psychological changes in the human body, thereby affecting people's moods and emotions [79]. In terms of the actual environment, we also found other details. For example, in hot weather during the summer, more people tend to gather in the shaded and comfortable areas of the park. When noise levels reach a certain point, people feel even more annoyed, ultimately affecting the park's overall satisfaction level [80]. Based on these findings, we recommend implementing measures to reduce the impact of environmental factors on the human body when designing and managing parks. For instance, incorporating some shading facilities [81] to mitigate the temperature impact during summer and regulating noise sources like grass cutting [82] and traffic can significantly enhance the park's overall satisfaction and service quality.

### 4.2. Shortcomings and Prospects

There are certain limitations to this study. Firstly, it was conducted within a limited time frame (summer 2022). Thus, its scope and applicability may be confined to warm environmental conditions. Secondly, the influence of other relevant variables, such as the SVF index, may contribute towards the analysis and accuracy of results. Thirdly, in future research, including other effective factors like soil moisture content could enhance the accuracy of conclusions concerning plant community spatial partitioning. Fourthly, regarding factors influencing shade provision by trees, the correlation between the cooling effect and thermal comfort may be more significant than acoustic comfort and can be explored in future analyses. Fifthly, although our experiments recruited healthy subjects, there were still some atypical groups among the tourist population, such as those who suffered from depression or hearing impairment. These groups perceive the environment differently from healthy individuals. Therefore, future research should focus on exploring the influence of the acoustic and thermal environment on the perception of atypical groups.

Lastly, considering their unique ecological and environmental characteristics and the socioeconomic and cultural differences among users, conducting more research in different climatic locations is necessary.

## 5. Conclusions

This study utilized questionnaire surveys and monitoring of distinct thermal and acoustic environments to analyze whether these environments impact subjective evaluation and attempted to determine the effects of thermal, and acoustic environments on thermal, acoustic, and overall environmental evaluations.

(1) Regarding thermal evaluation, the results showed that the thermal environment significantly impacted thermal sensation, thermal comfort, thermal acception and overall thermal vote. The thermal sensation increased significantly as the temperature rose, while thermal comfort, thermal acception and overall thermal vote declined significantly. Regarding acoustic environments, since the park is located in a low-noise environment with minimal noise fluctuation, LAeq had no significant impact on the thermal environment; its impact was only manifest in the TP's impact on thermal sensation, thermal comfort and overall thermal vote. Amongst the six major sound sources (water, bird song, rustling leaves, broadcasting music, conversations, and construction noise), those ranking higher positively impacted thermal evaluation. However, there was no interaction between UTCI and LAeq on thermal assessment.

(2) Regarding acoustic evaluation, it can be observed that LAeq in the sound environment significantly impacts the subjective loudness, acoustic harshness, acoustic Intensity, and acoustic Excitability of the sampling site. As the Laeq value increases, the negative evaluation of Subjective loudness, acoustic Harshness, acoustic Intensity, and acoustic Excitability also increases. Furthermore, the acoustic Comfort, acoustic Preference, acoustic Disorder, acoustic Coordination, and overall acoustic Vote in the sampling site are also significantly affected by TP. The higher the rank of TP, the higher the positive evaluation of acoustic Comfort, acoustic Preference, acoustic Disorder, acoustic Coordination, and overall acoustic Vote. The thermal environment also affects acoustic Harshness, acoustic Intensity, acoustic Excitability, and acoustic Coordination. As the temperature rises, the corresponding indicators tend to have negative evaluations. Moreover, the interaction effect between UTCI and Laeq significantly impacts Subjective loudness, acoustic Harshness, acoustic Intensity, and acoustic Excitability. As UTCI and LAeq values increase, they will move away from the neutral level.

(3) In terms of overall environmental assessment, the hot environment significantly influences the overall comfort vote, overall Annoyance vote and overall satisfaction vote in all sample sites. As the temperature rises, there is a trend of negative evaluation in the overall comfort vote, annoyance vote, and satisfaction vote. Regarding the sound environment, LAeq impacts the assessment of overall annoyance vote in the sample sites, and its evaluation increases in environments with higher sound pressure levels. TP significantly

influences the overall comfort vote, overall annoyance vote and overall satisfaction vote in all sample sites, and the more prominent rankings of TP result in more positive evaluations. In addition, the interaction between UTCI and LAeq also affects the evaluation of the overall annoyance vote and overall satisfaction vote, wherein as UTCI and LAeq increase, their evaluations tend to be negative and move away from the neutral level.

**Author Contributions:** Conceptualization, Y.C. and J.D.; methodology, Y.C., F.L. and X.L.; software, Y.C., J.L. (Jing Liu) and Z.C.; validation, Y.C., J.L. (Junyi Li) and K.S.; formal analysis, Y.C. and F.L.; investigation, Y.C., F.L., X.L., J.L. (Jing Liu), Z.C., K.S. and J.L. (Junyi Li); resources, Y.C.; data curation, Y.C.; writing—original draft preparation, Y.C.; writing—review and editing, Y.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by (1) Unit: Ministry of Science and Technology of the People's Republic of China. Green Urbanization across China and Europe: Collaborative Research on Key Technological Advances in Urban Forests, funding number 2021YFE0193200; (2) Unit: Ministry of Science and Technology of the People's Republic of China. Horizon 2020 strategic plan: CLEARING HOUSE-Collaborative Learning in Research, Information sharing, and Governance on How Urban tree-based solutions support Sino-European urban futures, funding number 821242.

**Data Availability Statement:** The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Basic information of subjects.

| No. | Gender | Age | Time Living in Fuzhou | No. | Gender | Age | Time Living in Fuzhou |
|---|---|---|---|---|---|---|---|
| 01 | Male | 31~40 | 16 | 16 | Male | 18~24 | 6 |
| 02 | Female | 31~40 | 12 | 17 | Female | 18~24 | 7 |
| 03 | Male | 25~30 | Less than 1 year | 18 | Female | 18~24 | Less than 1 year |
| 04 | Female | 25~30 | 10 | 19 | Male | 25~30 | Local |
| 05 | Male | 31~40 | 11 | 20 | Female | 25~30 | 12 |
| 06 | Male | 31~40 | 12 | 21 | Female | 31~40 | Less than 1 year |
| 07 | Male | 25~30 | Less than 1 year | 22 | Male | 18~24 | Local |
| 08 | Male | 25~30 | 12 | 23 | Male | 25~30 | 7 |
| 09 | Male | 25~30 | 2 | 24 | Female | 18~24 | Local |
| 10 | Male | 31~40 | Local | 25 | Female | 25~30 | Local |
| 11 | Male | 25~30 | 8 | 26 | Female | 25~30 | 12 |
| 12 | Male | 18~24 | 5 | 27 | Male | 25~30 | 7 |
| 13 | Female | 18~24 | 5 | 28 | Male | 25~30 | Less than 1 year |
| 14 | Male | 25~30 | 9 | 29 | Female | 18~24 | Local |
| 15 | Female | 25~30 | 7 | 30 | Female | 18~24 | Local |

**Table A2.** Subjective evaluations of the questionnaire surveys (TSV, TCV, TAV, OTV).

| Please Tick off One Response Alternatives for the Surrounding Thermal Environment | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Thermal Sensation | □ Cold | □ Cool | □ Neutral | □ warm | □ Hot |
| Thermal Comfort | □ Uncomfortable | □ Slightly Uncomfortable | □ Neutral | □ Slightly Comfortable | □ Comfortable |
| Thermal Acceptance | □ Unacceptable | □ Slightly unacceptable | □ Neutral | □ Slightly acceptable | □ Acceptable |
| Overall Thermal | □ Bad | □ Slightly bad | □ Neutral | □ Slightly good | □ Good |

**Table A3.** Subjective evaluations of the questionnaire surveys (SLV, ACV, APV, AHV, APlV, AFV, AIV, AEV, ADV, ACoV, OAV).

| Please Tick off the 11 Options That Match Your Feelings about the Surrounding Sound Environment | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Subjective Loudness | ☐ Quiet | ☐ Slightly quiet | ☐ Neutral | ☐ Slightly Loud | ☐ Loud |
| Acoustic Comfort | ☐ Uncomfortable | ☐ Slightly Uncomfortable | ☐ Neutral | ☐ Slightly Comfortable | ☐ Comfortable |
| Acoustic Preference | ☐ Unlike | ☐ Slightly unlike | ☐ Neutral | ☐ Slightly like | ☐ Like |
| Acoustic Harshness | ☐ Gentle | ☐ Slightly Gentle | ☐ Neutral | ☐ Slightly harsh | ☐ Harsh |
| Acoustic Pleasure | ☐ Unhappy | ☐ Slightly Unhappy | ☐ Neutral | ☐ Slightly happy | ☐ Happy |
| Acoustic Familiarity | ☐ Strange | ☐ Slightly Strange | ☐ Neutral | ☐ Slightly familiar | ☐ Familiar |
| Acoustic Intensity | ☐ Weak | ☐ Slightly weak | ☐ Neutral | ☐ Slightly strong | ☐ Strong |
| Acoustic Excitability | ☐ Calm | ☐ Slightly Calm | ☐ Neutral | ☐ Slightly excited | ☐ Excited |
| Acoustic Disorder | ☐ Monotonous | ☐ Slightly monotonous | ☐ Neutral | ☐ Slightly disordered | ☐ Disordered |
| Acoustic Coordination | ☐ Incoordinate | ☐ Slightly incoordinate | ☐ Neutral | ☐ Slightly coordinate | ☐ Coordinate |
| Overall Acoustic | ☐ Bad | ☐ Slightly bad | ☐ Neutral | ☐ Slightly good | ☐ Good |

**Table A4.** Subjective evaluations of the questionnaire surveys (OCV, OAnV, OSV).

| Overall, How Would You Describe the Present Surroundings Acoustic-Thermal Environment? | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Overall Comfort | ☐ Uncomfortable | ☐ Slightly Uncomfortable | ☐ Neutral | ☐ Slightly Comfortable | ☐ Comfortable |
| Overall Annoyance | ☐ Peaceful | ☐ Slightly Peaceful | ☐ Neutral | ☐ Slightly annoying | ☐ Annoying |
| Overall Satisfaction | ☐ Bad | ☐ Slightly bad | ☐ Neutral | ☐ Slightly good | ☐ Good |

## References


1. Ma, T.; Sun, S.; Fu, G.; Hall, J.W.; Ni, Y.; He, L.; Yi, J.; Zhao, N.; Du, Y.; Pei, T. Pollution exacerbates China's water scarcity and its regional inequality. *Nat. Commun.* **2020**, *1*, 650. [CrossRef] [PubMed]
2. Sun, S.; Zheng, X.; Liu, X.; Wang, Z.; Liang, L. Global pattern and drivers of water scarcity research: A combined bibliometric and geographic detector study. *Environ. Monit. Assess.* **2022**, *194*, 523. [CrossRef] [PubMed]
3. Awasthi, A.K.; Li, J.; Koh, L.; Ogunseitan, O.A. Circular economy and electronic waste. *Nat. Electron.* **2019**, *2*, 86–89. [CrossRef]
4. Fucheng, Y.; Jichang, Y.; Yuehong, W.; Dawei, C. Site environmental assessment to an old paint factory in China. *Environ. Monit. Assess.* **2008**, *139*, 93–106.
5. Kastner, J. The new baby boom. *Soap Perfum. Cosmet.* **2016**, *89*, 19.
6. Huang, Y.; Griffin, M.J. The discomfort produced by noise and whole-body vertical vibration presented separately and in combination. *Ergonomics* **2014**, *57*, 1724–1738. [CrossRef] [PubMed]
7. Huang, Y.; Griffin, M.J. The effects of sound level and vibration magnitude on the relative discomfort of noise and vibration. *J. Acoust. Soc. Am.* **2012**, *131*, 4558. [CrossRef]
8. Wang, C.; Geng, L.; Rodríguez-Casallas, J.D. How and when higher climate change risk perception promotes less climate change inaction. *J. Clean. Prod.* **2021**, *321*, 128952. [CrossRef]
9. Lai, H.F.; Huntley, R. Communicating about climate change–Who is listening, who isn't and why: Implications for medical professionals. *J. Paediatr. Child Health* **2021**, *57*, 1826–1829.
10. Daniel, S.; David, W.; Dirks, K.N.; Renata, M. Exploring the relationship between noise sensitivity, annoyance and Health-Related quality of life in a sample of adults exposed to environmental noise. *Int. J. Environ. Res. Public Health* **2010**, *7*, 3579.
11. King, R.P.; Davis, J.R. Community noise: Health effects and management. *Int. J. Hyg. Environ. Health* **2003**, *206*, 123–131. [CrossRef] [PubMed]
12. Fes, A.; Jt, B.; Tm, B. Mapping of transportation noise-induced health risks as an alternative tool for risk communication with local residents. *Appl. Acoust.* **2021**, *178*, 107987.
13. Giannaros, T.M.; Melas, D. Study of the urban heat island in a coastal Mediterranean City: The case study of Thessaloniki, Greece. *Atmos. Res.* **2012**, *118*, 103–120. [CrossRef]

14. Yang, B.; Yang, X.; Leung, L.R.; Zhong, S.; Qian, Y.; Zhao, C.; Chen, F.; Zhang, Y.; Qi, J. Modeling the impacts of urbanization on summer thermal comfort: The role of urban land use and anthropogenic heat. *J. Geophys. Res. D Atmos. JGR* **2019**, *124*, 6681–6697. [CrossRef]
15. de Souza e Silva, R.; da Silva, R.M.; de Freitas, A.F.; Dos Santos, J.S.; Santos, C.A.; de Lima, E.R. Thermal comfort conditions at microclimate scale and surface urban heat island in a tropical city: A study on Joao Pessoa city, Brazil. *Int. J. Biometeorol. J. Int. Soc. Biometeorol.* **2022**, *66*, 1079–1093. [CrossRef]
16. Loures, L.; Santos, R.; Panagopoulos, T. Urban parks and sustainable city Planning-The case of portimão, portugal. *WSEAS Trans. Environ. Dev.* **2007**, *3*, 171–180.
17. Di, L.; Yan, S.; Yue, Y.; Yi, H.; Chengyang, X. Urban park use and self-reported physical, mental, and social health during the COVID-19 pandemic: An on-site survey in Beijing, China. *Urban For. Urban Green.* **2023**, *79*, 127804.
18. Xu, M.; Hong, B.; Mi, J.; Yan, S. Outdoor thermal comfort in an urban park during winter in cold regions of China. *Sustain. Cities Soc.* **2018**, *43*, 208–220. [CrossRef]
19. Dong, W.; Ly, A.; Zb, C.; Yi, L.D.; Hy, E. Variations in outdoor thermal comfort in an urban park in the hot-summer and cold-winter region of China. *Sustain. Cities Soc.* **2021**, *77*, 103535.
20. Cureau, R.J.; Pigliautile, I.; Kousis, I.; Pisello, A.L. Multi-domain human-oriented approach to evaluate human comfort in outdoor environments. *Int. J. Biometeorol.* **2022**, *66*, 2033–2045. [CrossRef]
21. Yao, Y.A.; Jw, B.; Ye, H.C.; Chen, Q.D.; Qg, A.; Xun, L.A.; Ld, A.; Jz, E. Discovering the homogeneous geographic domain of human perceptions from street view images. *Landsc. Urban Plan.* **2021**, *212*, 104125. [CrossRef]
22. Stathopoulos, T.; Wu, H.; Zacharias, J. Outdoor human comfort in an urban climate. *Build. Environ.* **2004**, *39*, 297–305. [CrossRef]
23. Dumyahn, S.L.; Pijanowski, B.C. Soundscape conservation. *Landsc. Ecol.* **2011**, *26*, 1327–1344. [CrossRef]
24. Hong, X.; Cheng, S.; Liu, J.; Dang, E.; Wang, J.; Cheng, Y. The physiological restorative role of soundscape in different forest structures. *Forests* **2022**, *13*, 1920. [CrossRef]
25. Chen, Z.; Zhu, T.; Liu, J.; Hong, X. Before becoming a world heritage: Spatiotemporal dynamics and spatial dependency of the soundscapes in kulangsu scenic area, china. *Forests* **2022**, *13*, 1526. [CrossRef]
26. Hu, F.; Wang, Z.; Sheng, G.; Lia, X.; Chen, C.; Geng, D.; Hong, X.; Xu, N.; Zhu, Z.; Zhang, Z.; et al. Impacts of national park tourism sites: A perceptual analysis from residents of three spatial levels of local communities in Banff national park. *Environ. Dev. Sustain.* **2022**, *24*, 3126–3145. [CrossRef]
27. Kang, J. Soundscape in city and built environment: Current developments and design potentials. *City Built Environ.* **2023**, *1*, 1. [CrossRef]
28. Schulte-Fortkamp, B.; Fiebig, A.; Sisneros, J.A.; Popper, A.N.; Fay, R.R. (Eds.) *Soundscapes: Humans and Their Acoustic Environment*; Springer International Publishing: Berlin/Heidelberg, Germany, 2023.
29. Nikolopoulou, M. *Designing Open Spaces in the Urban Environment: A Bioclimatic Approach*; Centre for Renewable Energy Sources: Hong Kong, China, 2004.
30. Hong, X.; Liu, J.; Wang, G. Soundscape in urban forests. *Forests* **2022**, *13*, 2056. [CrossRef]
31. Carles, J.L.; Barrio, I.L.; de Lucio, J.V. Sound influence on landscape values. *Landsc. Urban Plan.* **1999**, *43*, 191–200. [CrossRef]
32. Carles, J.; Bernáldez, F.; Lucio, J.D. Audio-visual interactions and soundscape preferences. *Landsc. Res.* **1992**, *17*, 52–56. [CrossRef]
33. Wang, R.; Zhao, J. A good sound in the right place: Exploring the effects of auditory-visual combinations on aesthetic preference. *Urban For. Urban Green.* **2019**, *43*, 126356. [CrossRef]
34. Mei, Z.; Jian, K. Towards the evaluation, description, and creation of soundscapes in urban open spaces. *Environ. Plan. B Plan. Des.* **2007**, *34*, 68–86.
35. Yu, L.; Kang, J. Modeling subjective evaluation of soundscape quality in urban open spaces: An artificial neural network approach. *J. Acoust. Soc. Am.* **2009**, *126*, 1163–1174. [CrossRef] [PubMed]
36. Jiang, L.; Masullo, M.; Maffei, L. Effect of odour on multisensory environmental evaluations of road traffic. *Environ. Impact Assess. Rev.* **2016**, *60*, 126–133. [CrossRef]
37. Ba, M.; Jian, K. A laboratory study of the sound-odour interaction in urban environments. *Build. Environ.* **2019**, *147*, 314–326. [CrossRef]
38. Zhou, X.; Liu, Y.; Luo, M.; Zheng, S.; Zhang, X. Overall and thermal comfort under different temperature, noise, and vibration exposures. *Indoor Air* **2021**, *32*, e12915. [CrossRef]
39. Pellerin, N.; Candas, V. Combined effects of temperature and noise on human discomfort. *Physiol. Behav.* **2003**, *78*, 99–106. [CrossRef]
40. Yeyu, W.; Xiaodong, C.; Hui, L.; Xin, Z.; Xiang, Y.; Xian, D.; Xianting, L.; Bin, C. Influence of thermal and lighting factors on human perception and work performance in simulated underground environment. *Sci. Total Environ.* **2022**, *828*, 154455.
41. Li, H.; Zhu, Y.; Qin, O.; Cao, B. A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices. *Build. Environ.* **2012**, *49*, 304–309.
42. Kaplan, S. Meditation, restoration, and the management of mental fatigue. *Environ. Behav.* **2001**, *33*, 480–506. [CrossRef]
43. Yao, X.; Yu, K.; Zeng, X.; Lin, Y.; Ye, B.; Shen, X.; Liu, J. How can urban parks be planned to mitigate urban heat island effect in "Furnace cities" ? An accumulation perspective. *J. Clean. Prod.* **2022**, *330*, 129852. [CrossRef]
44. Junyi, L.; Ziluo, H.; Dulai, Z.; Yujie, Z.; Peilin, H.; Shanjun, H.; Wenqiang, F.; Weicong, F.; Zhipeng, Z. Effect of landscape elements on public psychology in urban park waterfront green space: A quantitative study by semantic segmentation. *Forests* **2023**, *14*, 244.

45. Lavandier, C.; Defréville, B. The contribution of sound source characteristics in the assessment of urban soundscapes. *Acta Acust. United Acust.* **2006**, *92*, 912–921.
46. Istvandity, L. Combining music and reminiscence therapy interventions for wellbeing in elderly populations: A systematic review. *Complement. Ther. Clin. Pract.* **2017**, *28*, 18–25. [CrossRef]
47. Blood, A.J.; Zatorre, R.J. Intensely pleasurable responses to music correlate with activity in brain regions implicated in reward and emotion. *Proc. Natl. Acad. Sci. USA* **2001**, *98*, 11818–11823. [CrossRef]
48. Ratcliffe, E.; Gatersleben, B.; Sowden, P.T. Bird sounds and their contributions to perceived attention restoration and stress recovery. *J. Environ. Psychol.* **2013**, *36*, 221–228. [CrossRef]
49. Zl, A.; Jian, K. Sensitivity analysis of changes in human physiological indicators observed in soundscapes. *Landsc. Urban Plan.* **2019**, *190*, 103593.
50. Jendritzky, G.; De, D.R.; Havenith, G. UTCI—Why another thermal index? *Int. J. Biometeorol.* **2012**, *56*, 421–428. [CrossRef]
51. Blazejczyk, K.; Epstein, Y.; Jendritzky, G.; Staiger, H.; Tinz, B. Comparison of UTCI to selected thermal indices. *Int. J. Biometeorol. J. Int. Soc. Biometeorol.* **2012**, *56*, 515–535. [CrossRef]
52. Pantavou, K.; Theoharatos, G.; Santamouris, M.; Asimakopoulos, D. Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI. *Build. Environ.* **2013**, *66*, 82–95. [CrossRef]
53. Fang, Z.; Lin, Z.; Mak, C.M.; Niu, J.; Tse, K.T. Investigation into sensitivities of factors in outdoor thermal comfort indices. *Build. Environ.* **2017**, *128*, 129–142. [CrossRef]
54. Peter, B.; Dusan, F.; Krzysztof, B.; Ingvar, H.; Gerd, J.; Bernhard, K.; Birger, T.; George, H. Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *Int. J. Biometeorol.* **2012**, *56*, 481–494.
55. Henshaw, V.A.; MCox, T.J. Route Planning a Sensory Walk: Sniffing out the Issues. In Proceedings of the Royal Geographical Society Annual Conference, Oxford, UK, 26–28 August 2009.
56. Tarlao, C.; Steffens, J.; Guastavino, C. Investigating contextual influences on urban soundscape evaluations with structural equation modeling. *Build. Environ.* **2020**, *188*, 107490. [CrossRef]
57. Ge, J.; Hokao, K. Research on the sound environment of urban open space from the viewpoint of soundscape-a case study of Saga Forest Park, Japan. *Acta Acust. United Acust.* **2004**, *90*, 555–563.
58. Kang, J.; Zhang, M. Semantic differential analysis of the soundscape in urban open public spaces. *Build. Environ.* **2010**, *45*, 150–157. [CrossRef]
59. Du, M.; Hong, B.; Gu, C.; Li, Y.; Wang, Y. Multiple effects of visual-acoustic-thermal perceptions on the overall comfort of elderly adults in residential outdoor environments. *Energy Build.* **2023**, *283*, 112813. [CrossRef]
60. Lam, C.; Yang, H.; Yang, X.; Liu, J.; Hang, J. Cross-modal effects of thermal and visual conditions on outdoor thermal and visual comfort perception. *Build. Environ.* **2020**, *186*, 107297. [CrossRef]
61. Tingkai, Y.; Yumeng, J.; Hong, J. Combined effects of the visual-thermal environment on the subjective evaluation of urban pedestrian streets in severely cold regions of China. *Build. Environ.* **2023**, *228*, 109895.
62. *International Standard 7726*; Ergonomics of the Thermal Environment Instruments and Method for Measuring Physical Quantities. IOS: Geneva, Switzerland, 1998.
63. Çeven, E.A.; Belkayali, N. Experiencing Urban Smells when Walking: Kastamonu city case. *Int. J. Urban Reg. Res.* **2023**, *47*, 237–257. [CrossRef]
64. Gage, S.H.; Axel, A.C. Visualization of temporal change in soundscape power of a Michigan lake habitat over a 4-year period. *Ecol. Inform.* **2014**, *21*, 100–109. [CrossRef]
65. Wang, F.; Huang, G.H.; Fan, Y.; Li, Y.P. Robust subsampling ANOVA methods for sensitivity analysis of water resource and environmental models. *Water Resour. Manag.* **2020**, *34*, 3199–3217. [CrossRef]
66. Vaus, D. *Surveys in Social Research*; Routledge: Oxford, UK, 1986.
67. Callan, A.; Callan, D.E.; Ando, H. Neural correlates of sound externalization. *Neuroimage* **2013**, *66*, 22–27. [CrossRef] [PubMed]
68. Lee, H.M.; Liu, Y.; Lee, H.P. Assessment of acoustical environment condition at urban landscape. *Appl. Acoust.* **2020**, *160*, 107126. [CrossRef]
69. Taghipour, A.; Sievers, T.; Eggenschwiler, K. Acoustic comfort in virtual inner yards with various building facades. *Int. J. Environ. Res. Public Health* **2019**, *16*, 249. [CrossRef] [PubMed]
70. Ma, K.W.; Mak, C.M.; Wong, H.M. Effects of environmental sound quality on soundscape preference in a public urban space. *Appl. Acoust.* **2021**, *171*, 107570. [CrossRef]
71. Steele, D.; Bild, E.; Tarlao, C.; Guastavino, C. Soundtracking the public space: Outcomes of the musikiosk soundscape intervention. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1865. [CrossRef]
72. Jin, Y.; Jin, H.; Kang, J. Combined effects of the thermal-acoustic environment on subjective evaluations in urban squares. *Build. Environ.* **2020**, *168*, 106517. [CrossRef]
73. Hao, Y.; Kang, J.; Wörtche, H. Assessment of the masking effects of birdsong on the road traffic noise environment. *J. Acoust. Soc. Am.* **2016**, *140*, 978–987. [CrossRef]
74. Mohammadzadeh, N.; Karimi, A.; Brown, R.D. The influence of outdoor thermal comfort on acoustic comfort of urban parks based on plant communities. *Build. Environ.* **2023**, *228*, 109884. [CrossRef]
75. Yang, W.; Moon, H.J. Cross-modal effects of noise and thermal conditions on indoor environmental perception and speech recognition. *Appl. Acoust.* **2018**, *141*, 1–8. [CrossRef]

76. Chen, H.; Hong, B.; Qu, H.; Geng, Y.; Su, M. Effects of Acoustic Perception on Outdoor Thermal Comfort in Campus Open Spaces in China's Cold Region. *Buildings* **2022**, *12*, 1518. [CrossRef]
77. Cerwn, G. Urban soundscapes: A quasi-experiment in landscape architecture. *Landsc. Res.* **2016**, *41*, 481–494. [CrossRef]
78. Nagano, K.; Horikoshi, T. New comfort index during combined conditions of moderate low ambient temperature and traffic noise. *Energy Build.* **2005**, *37*, 287–294. [CrossRef]
79. Son, Y.J.; Chun, C. Research on electroencephalogram to measure thermal pleasure in thermal alliesthesia in temperature step-change environment. *Indoor Air* **2018**, *28*, 916–923. [CrossRef] [PubMed]
80. Yu, T.H.; Behm, H.; Bill, R.; Kang, J. Validity of VR technology on the smartphone for the study of wind park soundscapes. *ISPRS Int. J. Geo Inf.* **2018**, *7*, 152. [CrossRef]
81. Lin, T.P.; Tsai, K.T.; Liao, C.C.; Huang, Y.C. Effects of thermal comfort and adaptation on park attendance regarding different shading levels and activity types. *Build. Environ.* **2013**, *59*, 599–611. [CrossRef]
82. Mallick, Z.; Badruddin, I.A.; Hussain, M.; Ahmed, N.; Kanesan, J. Noise characteristics of grass-trimming machine engines and their effect on operators. *Noise Health* **2009**, *11*, 98–102.


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

*forests*

MDPI

*Article*

# Effects of Deciduous Forests on Adolescent Emotional Health in Urban Areas: An Example from the Autumn Ginkgo Forest in Chengdu

**Linjia Wu [1], Shixian Luo [2], Di Li [3], Qibing Chen [4,*], Jingting Li [1] and Jiacai Wen [1]**

[1] College of Art, Sichuan Tourism University, Chengdu 610100, China; wulinjia@sctu.edu.cn (L.W.); 0000120@sctu.edu.cn (J.W.)
[2] Graduate School of Horticulture, Chiba University, Chiba 263-8522, Japan; 19hd4106@student.gs.chiba-u.jp
[3] Geophysical Exploration Brigade of Hubei Geological Bureau, Wuhan 430100, China
[4] College of Landscape Architecture, Sichuan Agricultural University, Chengdu 625014, China
* Correspondence: cqb@sicau.edu.cn

**Abstract:** Many studies have shown that urban green spaces can promote emotional health. Deciduous forest is an important landscape and ecological resource of the city. However, the emotional impact of different behavior patterns in this kind of natural space with obvious seasonal changes are rarely discussed. This study explores the emotional feedback of two typical behavior patterns within an urban landscape forest in autumn: sitting and walking. We recruited 80 volunteers and divided them into a sitting viewing group (group S) and a walking viewing group (group W). On the premise of gender balance, they were randomly assigned to a natural path under a *Ginkgo biloba* forest in autumn for 15 min of viewing. Physiological and psychological indicators were used for monitoring. Blood pressure, heart rate and electroencephalography (EEG) were used for physiological indicators, and a POMS questionnaire was used for psychological indicators. A paired *t*-test and one-way ANOVA were used to analyze the physiological parameters of the two experimental groups, and a paired Wilcoxon signed-rank sum test was used to analyze the differences in psychological indexes between the two behavior groups. The results showed that the diastolic blood pressure and pulse of the sitting group decreased significantly under the seasonal deciduous forest, and the walking group attained higher "Engagement", "Excitement", and "Relaxation". In the absolute α and β waves, there were significant differences in the parietal P8 channels between the sitting and walking groups, and significant differences in the RAB indicators of the AF3, F7, P7, FC5, FC6, F3 and T7 channels. The two behavior patterns can effectively reduce negative mood, and the "Vigor" mood in the walking group was significantly increased, which was significantly better than that of the sitting group in reducing negative mood. These results enrich research on the influence on emotional health in the field of seasonal green-space restoration. The differences of different behavior patterns can provide guidance for planning urban landscape forest construction and activity facilities.

**Keywords:** urban landscape forest; seasonality; blood pressure; EEG; POMS; teenagers; mood

**Citation:** Wu, L.; Luo, S.; Li, D.; Chen, Q.; Li, J.; Wen, J. Effects of Deciduous Forests on Adolescent Emotional Health in Urban Areas: An Example from the Autumn Ginkgo Forest in Chengdu. *Forests* **2023**, *14*, 1099. https://doi.org/10.3390/f14061099

Academic Editor: Arne Arnberger

Received: 25 March 2023
Revised: 17 May 2023
Accepted: 18 May 2023
Published: 26 May 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

Emotional stress in urban environments is a constant, urgent problem in urban public health [1,2]. Neurological diseases and burnout from attention consumption and mental fatigue [3,4] are increasing among youths [5] in high-density physical environments. Teenagers are an active group in the city and are more likely to experience emotional disorders caused by academic and social pressures during their growth [6,7]. Effective emotional regulation strategies can help teenagers develop adaptive responses and reduce the risk of emotion-related physical and psychological diseases [8–10]. Research on urban green spaces and public health under the interdisciplinary trend of urban planning

shows that green space plays an important role in health promotion and improving well-being [11,12]. Although the environment itself cannot cure a disease, spending time in natural environments may increase positive emotions [13]. Researchers have previously conducted empirical and differential explorations of the physiological and psychological improvement effects of experiencing green environments on adolescents, including studies on landscape categories [14], changes in structural elements [15], and different sensory stimuli [16,17]. In addition, studies on land restoration and preferences showed the significant influence of seasonal characteristics on the appearance of landscape structure [18], visual preference [19], and landscape stress recovery quality [20]. However, discussion on landscape forests, an important part of urban natural capital, is lacking, especially landscape forests affected by seasons [21,22]. In addition, i in terms of exploring the impact of the forest environment on health, previous studies have confirmed that terpene structures in forest environments may be the reasons for positive health effects [23]. Larger parks such as forests have better health outcomes [24], and further explored self-reported and simple physiological measurements of meditation behavior patterns. The complexity of landscapes necessitates more accurate measurement tools to study the effects of landscapes on emotions. Therefore, it is necessary to conduct more accurate measurements based on applied scientific test validation to provide more scientific and effective guidance for urban forest construction.

Behavior is an important link between humans and green space [25]. Positive emotions have important effects on human health and well-being, and the biological state of emotion is related to the nervous system [26]. There is a close relationship between participants' behavioral responses and emotions [27]. Emotional activity is also a common aspect widely considered in green-space research [25]. Even in the same environment, different behavior patterns generate different emotional feedback [28]. Previous studies have used a combination of physiology [17,29] and psychology [30–32] to measure the emotional feedback of participants. For example, walking in the forest has a relaxing effect on young people [33], and observing nature can increase satisfaction [34]. Regarding emotional differences, there is a significant negative correlation between meditation, emotion and behavioral responses [27]. Walking in green space is more conducive to decompression, while sitting is more conducive to recovering attention [25]. Different behavior patterns in urban natural environments can induce or trigger emotions to some extent. However, most of these studies are based on the green and vibrant natural environment, and the influence of different behavior patterns on recreational benefits is not addressed. Because the season has been found to have an important impact on people's mood in stress recovery experiments [35], especially in an urban natural environment with obvious seasonal changes, basic research on spontaneous behavior and health in seasonal green spaces is of great value in the construction of urban natural environments.

In addition, in the discussion of emotions in relation to urban forests, the healthy development of an urban landscape forest has always been considered conducive to human health, including the positive emotions obtained through contact with nature [36]. Seasonal trees can affect visual preferences [19], and these trees can undergo subtle to obvious visual changes throughout seasonal changes [37]. Some patients with psychosis show more positive facial expressions when viewing green trees than when viewing tree images with autumn colors [38], and golden leaves cause positive psychophysiological reactions [39], which may indicate the potential for seasonal urban landscape forests to improve moods as a public health resource. Although any behavior conducted while being exposed to such resources may have health promotion effects, it is still worth exploring the additional emotional promotion benefits obtained by determining different behavior patterns in urban seasonal landscape forests.

*Purpose and Assumptions*

The purpose of this study was to explore the influences and differences of two different behavior modes of experiencing seasonal urban landscape forests—sitting and walking—on

emotional indicators in adolescents. This study aimed to provide a reference for seasonal behavior induction and a health basis for urban green-space construction. Based on existing studies, we used comprehensive physiological and psychological indicators to evaluate the emotional state of volunteers. The physiological indicators were blood pressure (diastolic and systolic), heart rate and EEG. We used three emotional indicators provided or calculated by Emotiv EPOC+. The first is the six neuroemotional parameters "engagement", "excitement", "stress", "relaxation", "interest" and "focus". The second is the RAB index, which was found to be closely related to behavior in previous studies [40]. The third comprises 14 channels in which the characteristic parameters evaluated by specific stimuli [41,42] are presented as widely used α and β waves. The psychological indicators were calculated using the POMS scale. The key objectives of the study were (1) to explore the differences in different behavior patterns in seasonal urban landscape forests by comprehensively assessing physiological and psychological indicators; (2) to identify significant differences between the two behavioral patterns discussed in the study and the reasons for these differences; and (3) based on the above two issues, provide a theoretical basis for urban forest design, management and activity strategy planning.

## 2. Materials and Methods

### *2.1. Study Site and Participants*

The experimental site is located in the largest ginkgo garden in Chengdu, Sichuan Province (103°86′44″ E and 30°58′50″ N). The ginkgo garden is part of an artificial plantation in which over 13.33 hectares of ginkgo trees of different ages are planted. *Ginkgo biloba* L. is a unique deciduous tree in China and a representative urban deciduous tree species in Chengdu. The leaf shape is beautiful, and its color changes from green to golden yellow in autumn. *Ginkgo biloba* L. is China's most important and common urban greening material and can eliminate the effects caused by unfamiliar environments. Our experimental site is an important urban viewing place in the city. The research area provides a realistic experience since tourists and footpaths can be seen in the park. A forestland with a relatively uniform stand, a canopy density of 0.45 and a relatively quiet environment (noise value range: 59.91 ± 10.48–64.38 ± 5.82, noise meter CEN-TER322) was selected as the experimental site. Wheelchair accessibility [43] and general accessibility [44] can affect emotional responses in natural environments. To facilitate an emotional impression of the natural environment as a pure forest, we chose a common green space similar to downstream forest trails (general trail width 1.5–3 m) with ginkgo biloba trees on both sides as the candidate for the experimental site; such areas have been confirmed as effective in previous studies. The final section of the experimental site has a natural path. A U-shaped footpath with an average width of 3.2 m and a total length of 166 m was the experimental area used to assess emotional influence (Figure 1).

Since there is no specific sample size stipulated for EEG experiments, we referred to the minimum sample size requirement [15] and recruited 80 young adults (40 males and 40 females, average age (23.42 ± 1.03), from Sichuan Agricultural University through campus posters and online advertising. After the experiment, they received corresponding compensation (RMB 30). We divided the participants into the sitting (Group S) and walking (Group W) groups according to their behavior patterns, with twenty men and twenty women in each group. Before the experiment, the study staff sent the detailed experimental process to the volunteers. All subjects were required to be right-handed [45] and have no history of long-term drug and alcohol abuse, to prevent differences in brain hemispheres from influencing the results. Drinking alcohol, strenuous exercise and taking drugs were prohibited on the day before the experiment to ensure the accuracy of the experiment.

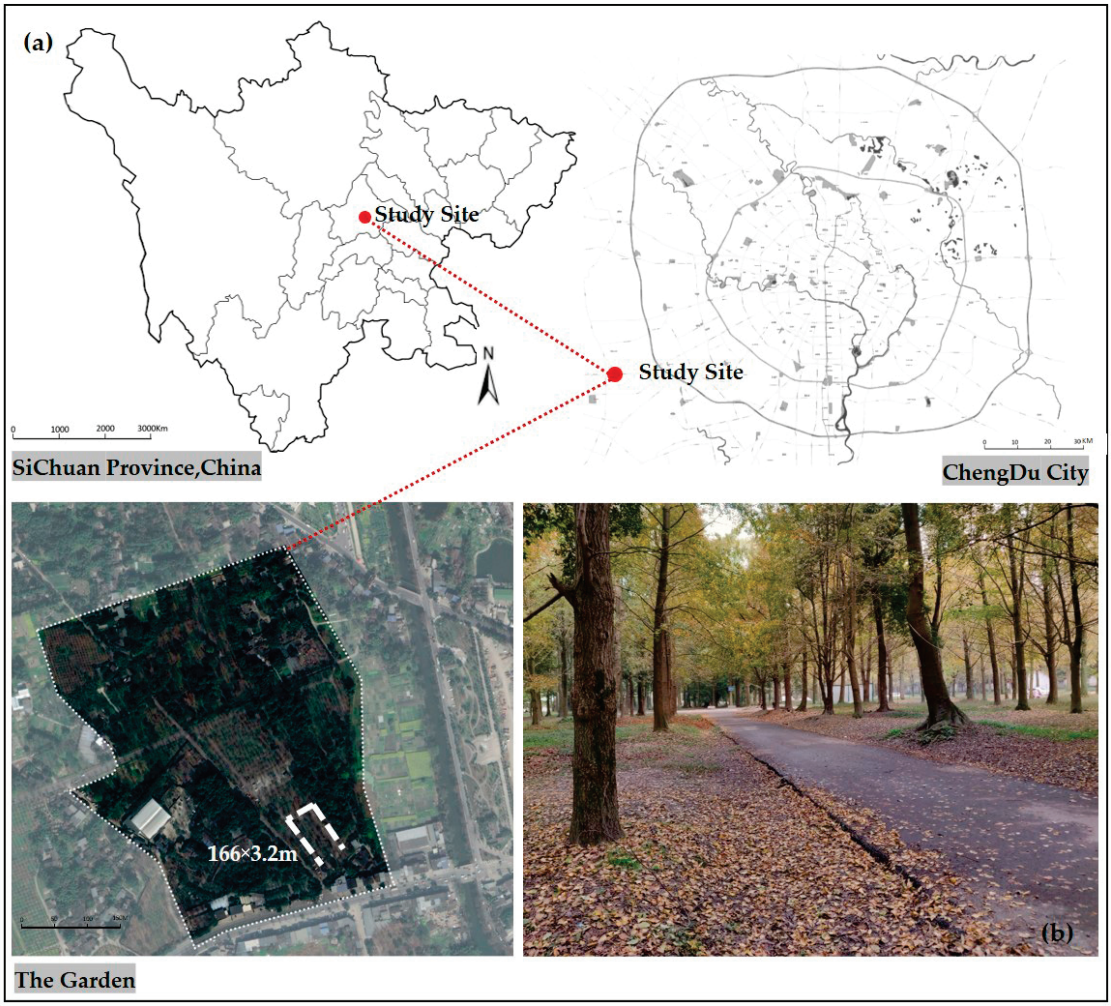



**Figure 1.** Study site. (**a**) Map of the experimental location and of the studied sites. (**b**) Current situation map of the experimental site.

### *2.2. Measure*

#### 2.2.1. Physiological Measurement

Physiological indices: Blood pressure, pulse and EEG were used to observe the physiological differences between the two behavioral groups. Blood pressure, including systolic (mmHg) and diastolic (mmHg), and pulse rate (bmp) were measured using a sphygmomanometer (Omron, HEM-6322T, Omron, Tokyo, Japan). Systolic and diastolic blood pressure increase when a person is stressed and decrease when he or she is relaxed, while the pulse rate increases when the body is in motion or emotionally excited. EEG is a common method widely used to evaluate the effect of forest therapy [31,46,47]. EEG records changes in electrical waves during brain activity. The instrument is noninvasive and has the practical advantages of being low-cost and quick, without the need for conductive gel [48]. Wearing the EEG equipment provides data from four brain lobe regions (namely, i.e., the frontal, temporal, parietal and occipital lobes). Fourteen channels (AF4, AF3, F3, F4, F7, F8, FC5, FC6, T7, T8, P7, P8, O1 and O2) were recorded. The data were analyzed using Affective, the EEG equipment's software suite, which assigns and defines six emotion parameter labels; each individual's data can be standardized on a scale of 0 to 1 [45].

#### 2.2.2. Psychometrics

The Profile of Mood States (POMS) psychological questionnaire was used to measure the participants' psychological state. The abbreviated POMS is another reliable and valid instrument for measuring mentality, including 40 adjectives rated on a 0–4 scale (0 = not at

all; 4 = extremely). These adjectives can be consolidated into seven effective dimensions: Tension-Anxiety (T-A), Depression (D), Anger-Hostility (A-H), Vigor (V), Fatigue (F), Confusion (C) and Self-esteem (S). Three psychological indicators can also be obtained: positive, negative, and total mood (TMD) [49].

### 2.3. Experimental Procedure

This research is divided into two stages. The first stage consisted of the indoor parts, where volunteers at Sichuan Agricultural University completed the questionnaire in a classroom (temperature 22–26 °C, humidity 49%–55%). The questionnaire included social demographic characteristics and an informed consent form provided to the volunteers after the staff transported them to the experimental site, which was a ~30 min drive away. Outdoor measurements (outdoor temperature: 15.44 ± 1.14 °C, outdoor humidity: 75.92 ± 4.40%) were then taken. After reaching the experimental site, the volunteers sat quietly with their eyes closed for 5 min to reduce external influences, such as artifacts. The volunteers were then led to the experimental path, where they would be fitted with the EEG device. The EEG instrument was installed on the volunteer's head. While wearing the device, the volunteers were instructed to feel the environment quietly and were not permitted to talk, eat, or use mobile phones. The volunteers were instructed to sit or walk for 15 min in different groups wearing the emotiv-EPOC+. The staff left after turning on the emotiv-EPOC+ devices to record the EEG data. After the experiment ended, the staff removed the instrument and instructed the volunteers to rest for 5 min before returning to school (Figure 2). The staff grouped all subjects to conduct the experiment sequence, in which Group S and Group W participated simultaneously. The experiment took place in November 2020 over three days from 9 am to 6 pm each day. The experimental procedure was conducted in accordance with the ethical standards of the National Research Council and the Herkey Declaration and was approved by the local Ethics Committee of the College of Landscape Architecture, Sichuan Agricultural University.

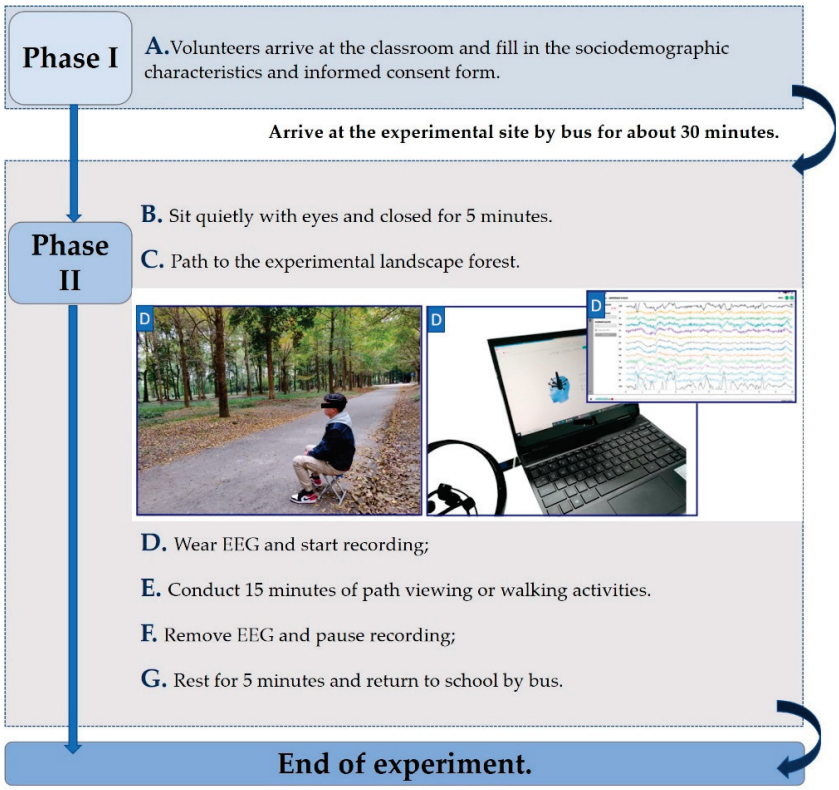



**Figure 2.** Experimental procedure.

### 2.4. Data Statistics and Analysis

Statistical and data analyses were conducted using Excel 2016 and SPSS 20.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics and chi-square tests were used to test the differences in the sociodemographic characteristics of the study samples, and paired t-tests were used to compare the average physiological parameters of the two behavioral groups and explore their significance level. EEG data were processed under the conditions of normal distribution and compliance with normal distribution; a one-way analysis of variance (ANOVA) was used to evaluate the significance of the six mood indicators and RAB indicators. The paired Wilcoxon signed-rank sum test was used to analyze the difference in psychological indicators between the two behavioral groups.

## 3. Results

### 3.1. Physiological Results

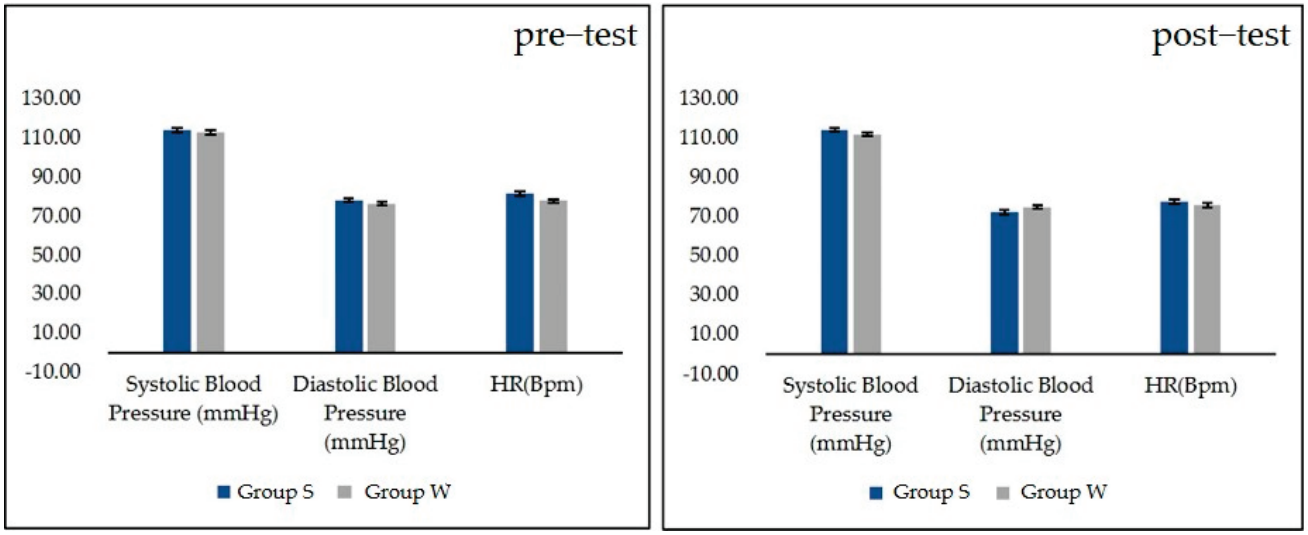
#### 3.1.1. Blood Pressure, Pulse Rate

Table 1 shows the changes in blood pressure and heart rate before and after the two behavior modes. As shown, no significant changes in systolic blood pressure were observed in Group S (113.80 ± 14.94 pre and 114.10 ± 13.64 post, $p > 0.05$). The diastolic blood pressure decreased significantly (78.02 ± 11.99 pre and 72.27 ± 10.06 post, $p < 0.01$) by 5.76. The pulse rate was significantly decreased (81.37 ± 14.77 pre and 77.44 ± 9.89 post, $p < 0.05$) by 3.93. There were no significant changes in diastolic (112.63 ± 15.80 pre and 111.75 ± 13.10 post, $p > 0.05$) or systolic (76.41 ± 9.94 pre and 74.86 ± 9.61 post, $p > 0.05$) blood pressure or pulse (77.68 ± 12.30 pre and 75.72 ± 11.38 post, $p > 0.05$) in Group W. As shown in Figure 3, no significant difference was observed between the two behavioral groups in diastolic blood pressure, systolic blood pressure, and pulse before and after viewing (paired $t$ test, $p > 0.05$).

**Table 1.** Changes in blood pressure and pulse rate before and after in Group S and Group W.

| Group S | | | | | | |
|---|---|---|---|---|---|---|
| **Physiological Indexes** | **Pre-Test** | | **Post-Test** | | **Rate of Change** | ***p*** |
| | **Mean** | **S.D.** | **Mean** | **S.D.** | | |
| Systolic blood pressure (mmHg) | 113.80 | 14.94 | 114.10 | 13.64 | 0.29 | 0.897 |
| Diastolic blood pressure (mmHg) | 78.02 | 11.99 | 72.27 | 10.06 | −5.76 | 0.008 **[1] |
| HR (bpm) | 81.37 | 14.77 | 77.44 | 9.89 | −3.93 | 0.024 *[2] |
| **Group W** | | | | | | |
| **Variable** | **Pre-Test** | | **Post-Test** | | **Rate of Change** | ***p*** |
| | **Mean** | **S.D.** | **Mean** | **S.D.** | | |
| Systolic blood pressure (mmHg) | 112.63 | 15.80 | 111.75 | 13.10 | −0.88 | 0.925 |
| Diastolic blood pressure (mmHg) | 76.41 | 9.94 | 74.86 | 9.61 | −1.55 | 0.374 |
| HR (bpm) | 77.68 | 12.30 | 75.72 | 11.38 | −1.97 | 0.134 |

**[1] $p < 0.01$. *[2] $p < 0.05$.




(**a**) (**b**)

**Figure 3.** Difference test of Group S and Group W paired samples. (**a**) Differences in paired samples of pre−test between S and W groups. (**b**) Differences in paired samples of post−test between S and W groups.

3.1.2. Emotional indicators

Figure 4 shows six emotional parameter values for two behavior patterns. As shown, the "engagement" and "excitement" (0.60 ± 0.08 and 0.32 ± 0.16, respectively) levels of Group S were significantly lower than those of Group W (0.67 ± 0.09; 0.44 ± 0.13). Among the "Relaxation" emotional parameters, the levels of Group W (0.40 ± 0.07) were significantly higher than those of Group S (0.28 ± 0.07; $p = 0.000$), and the levels of the "Interest" emotional parameter in Group S (0.58 ± 0.06) were significantly higher than those in Group W (0.53 ± 0.04; $p < 0.01$). No significant differences in the "Stress" and "Focus" emotional parameters were observed between the two groups.

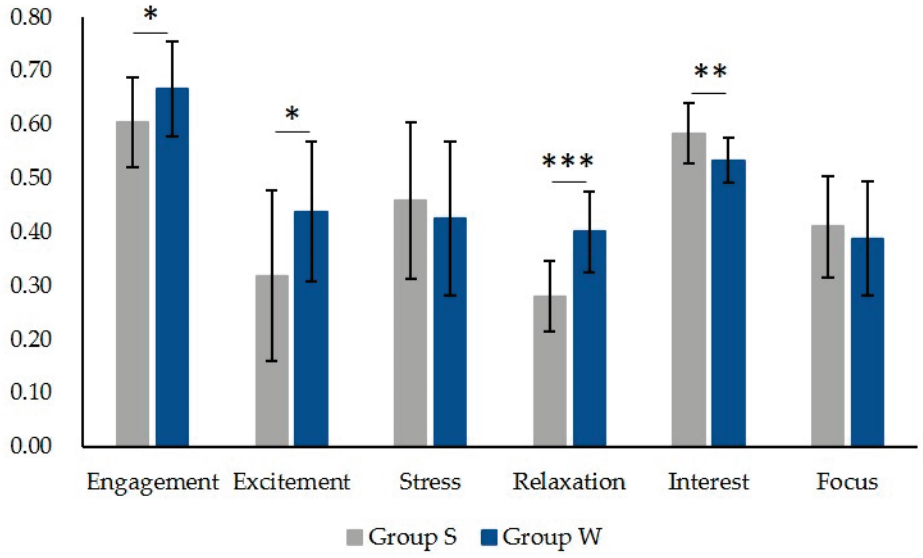



**Figure 4.** Six emotional parameter values of Group S and Group W (*** $p < 0.001$. ** $p < 0.01$. * $p < 0.05$).

Figure 5 shows the difference in RAB index values of the 14 channels in the four brain regions, mainly distributed in the frontal, temporal, and parietal lobes. Specific

differences were observed in the AF3, F7 and P7 changes, which were significantly lower in Group S than in Group W ($p < 0.01$). The FC5, FC6, F3 and T7 channels showed significant differences between the behavior patterns ($p < 0.01$), and the RAB index values for Group S were significantly lower than those for Group W in the above four channels. There were no significant differences in the O1 and O2 channels of the occipital lobe.

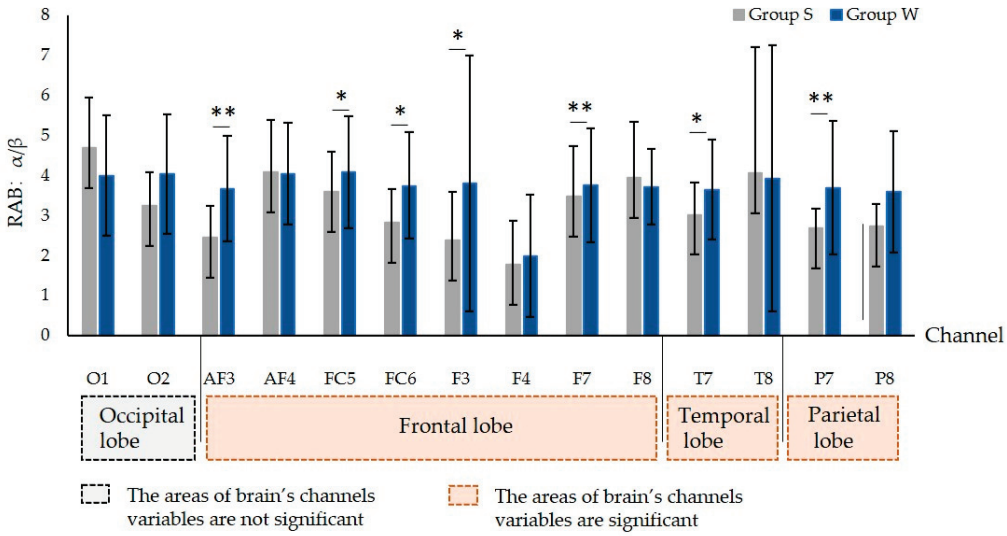



**Figure 5.** The corresponding RAB index values of the 14 brain channels of the Group S and Group W participants (** $p < 0.01$. * $p < 0.05$).

Table 2 shows the absolute α and β waves for the 14 electrodes under different behavioral patterns in an urban seasonal landscape forest. As shown in the table, the O2 and P8 electrodes in the occipital and parietal lobes, respectively, showed significant differences in the absolute α wave ($p < 0.05$). In the absolute β wave, the FC6, F4 and P8 electrodes showed significant differences ($p < 0.05$). These electrodes were located in the frontal and parietal lobes. There was no difference between the two groups of electrodes in the temporal lobe region of the brain.

**Table 2.** Absolute α and β wave values in different behavior patterns.

| The Areas of Brain | Electrodes | α Wave | | | | | β Wave | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Group S | | Group W | | Sig. | Group S | | Group W | | Sig. |
| | | Mean | SD | Mean | SD | | Mean | SD | Mean | SD | |
| Occipital lobe | O1 | 7.98 | 1.90 | 13.27 | 3.00 | 0.55 | 1.70 | 3.35 | 3.32 | 1.68 | 0.39 |
| | O2 | 5.82 | 2.28 | 14.36 | 2.37 | 0.026 * | 1.80 | 2.20 | 3.56 | 7.10 | 0.30 |
| Frontal lobe | AF3 | 2.07 | 2.35 | 20.43 | 1.33 | 0.06 | 0.84 | 0.66 | 5.57 | 1.47 | 0.05 |
| | AF4 | 8.28 | 1.02 | 34.62 | 1.03 | 0.08 | 2.03 | 2.60 | 8.56 | 14.90 | 0.06 |
| | FC5 | 4.13 | 1.10 | 15.02 | 3.96 | 0.10 | 1.15 | 2.14 | 3.69 | 8.42 | 0.20 |
| | FC6 | 4.39 | 2.85 | 24.35 | 1.48 | 0.04 | 1.55 | 1.36 | 6.50 | 10.50 | 0.043 * |
| | F3 | 1.94 | 1.18 | 10.46 | 2.85 | 0.13 | 0.81 | 0.86 | 2.75 | 5.46 | 0.13 |
| | F4 | 6.35 | 1.06 | 7.60 | 3.28 | 0.28 | 3.59 | 2.11 | 3.82 | 7.81 | 0.035 * |
| | F7 | 4.68 | 2.85 | 14.14 | 2.43 | 0.14 | 1.35 | 1.96 | 3.77 | 5.81 | 0.09 |
| | F8 | 11.16 | 1.81 | 10.11 | 1.40 | 0.84 | 2.83 | 3.14 | 2.72 | 3.27 | 0.91 |
| Temporal lobe | T7 | 2.49 | 0.03 | 18.00 | 3.19 | 0.08 | 0.83 | 0.68 | 4.93 | 9.48 | 0.06 |
| | T8 | 14.97 | 2.59 | 33.26 | 2.92 | 0.18 | 3.69 | 5.31 | 8.47 | 3.03 | 0.14 |
| Parietal lobe | P7 | 1.06 | 1.99 | 11.28 | 2.82 | 0.10 | 0.39 | 0.64 | 3.05 | 6.17 | 0.06 |
| | P8 | 6.27 | 5.92 | 21.33 | 2.40 | 0.031 * | 2.29 | 1.97 | 5.93 | 1.56 | 0.03 * |

* $p < 0.05$.

### *3.2. Psychometric Results*

Pretest and posttest comparisons were made according to the seven emotional states in the POMS scale. As shown in Figure 6, Group S can effectively improve "Tension-Anxiety" (0.66 ± 0.56 pre and 0.37 ± 0.39 post, $p < 0.05$), "Depression" (0.36 ± 0.45 pre and 0.13 ± 0.26 post, $p < 0.05$) and "Fatigue" (0.92 ± 0.55 pre and 0.56 ± 0.57 post, $p < 0.05$) emotions. The mood of "depression" (0.57 ± 0.64 pre and 0.17 ± 0.32 post, $p < 0.05$), "Anger-Hostility" (1.38 ± 1.75 pre and 0.48 ± 0.46 post, $p < 0.05$), "Fatigue" (1.09 ± 0.78 pre and 0.59 ± 0.44 post, $p < 0.05$) and "Self-Esteem" (0.84 ± 0.78 pre and 0.29 ± 0.31 post, $p < 0.05$) in Group W decreased significantly, whilst the mood of "Vigor" (2.17 ± 0.70 pre and 2.65 ± 0.86 post, $p < 0.05$) increased significantly.

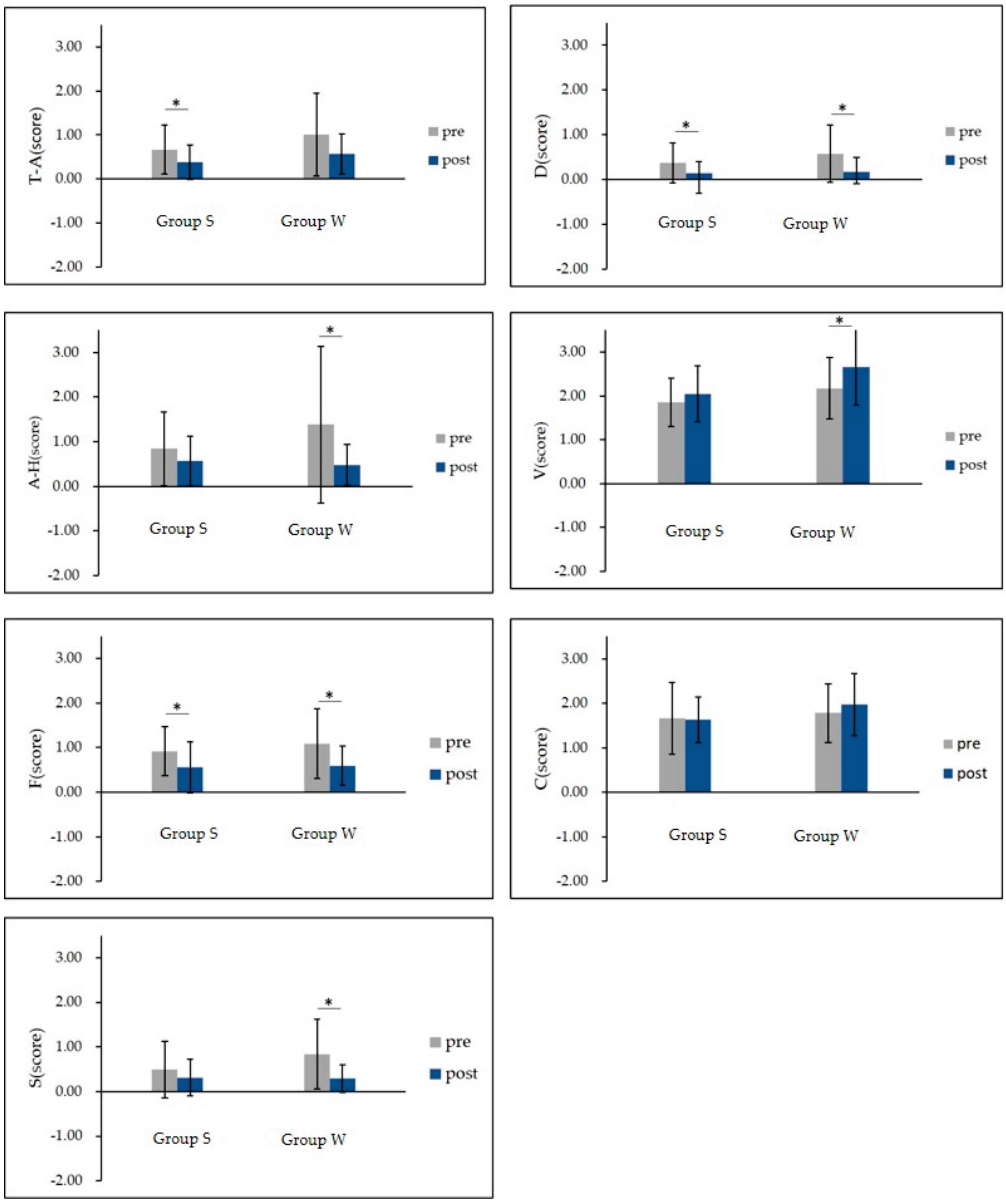



**Figure 6.** Emotional states in Group S and Group W (T−A: T scores for tension-anxiety; D: depression; A−H: anger−hostility; V: vigor; F: fatigue; C: confusion; S, self−esteem; * $p < 0.05$).

As shown in Figure 7, negative moods were significantly reduced in Group W (27.40 ± 14.66 pre and 11.70 ± 5.62 post, $p < 0.05$) in comparison with Group S (18.30 ± 15.99 pre and 10.70 ± 6.50 post, $p > 0.05$). The TMD of the two behavior groups decreased significantly before and after (Group S 98.90 ± 18.30 pre and 90.25 ± 7.30 post, $p < 0.05$, Group W

105.45 ± 16.25 pre and 85.90 ± 9.88 post, $p < 0.05$), and there was no significant change or difference in promoting positive emotion ($p > 0.05$).

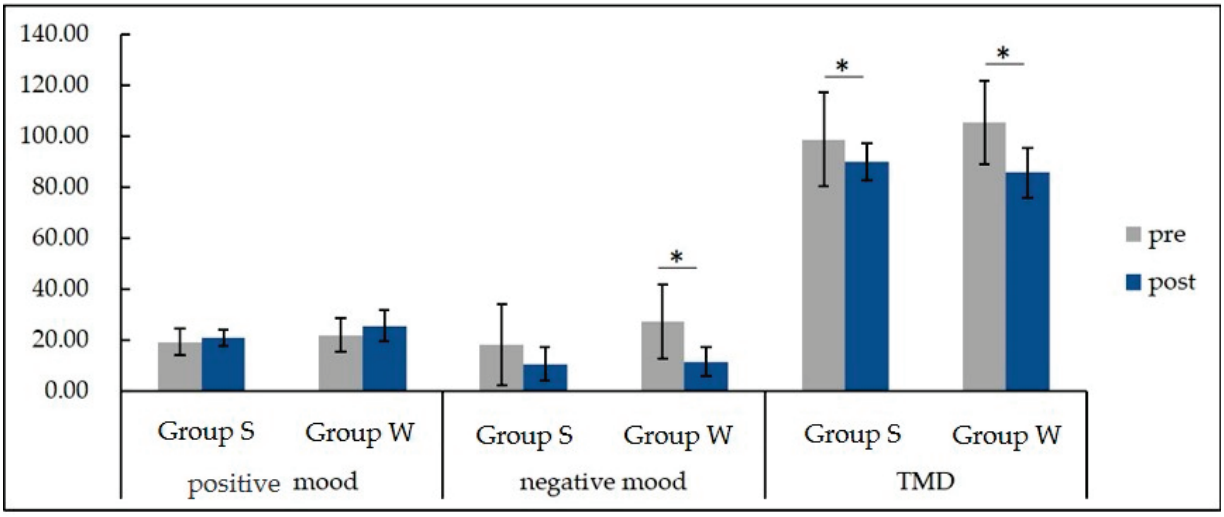



**Figure 7.** Mood state values in Group S and Group W (* $p < 0.05$).

## 4. Discussion

### *4.1. Physiological Index Influence*

Adolescents are more likely to experience emotional problems characterized by emotional disorders in their daily lives [50,51]. Given the significant healthy-life-promoting effect of green space [52], it is of great significance to study the differences between emotion induction strategies in green spaces in terms of physiological responses. The results showed that the diastolic blood pressure and pulse of Group S decreased significantly ($p < 0.01$), while the systolic blood pressure, diastolic blood pressure and pulse of Group W did not change ($p > 0.05$). When excluding environmental differences, different behavior patterns produced different physiological feedback, consistent with the findings of Chorong, S [53], Ulrich [54] and others. In addition, compared with Group W, Group S demonstrated increased parasympathetic nerve activity and inhibited sympathetic nerve activity, and their heart rates tended to be flat, which is more conducive to the reduction of pulse and pressure symptoms. Previous studies have proven that observing nature can increase satisfaction, and walking can increase vitality [28]. We studied older adolescents; in comparison with younger people, this group shows more attention to and awareness of landscape changes, and the season significantly impacts the pressure-relieving effects of the landscape [35]. The behaviors participated in by Group W resulted in their exposure to a continuously changing landscape, while Group S remained in one place; Group W communicated the effects of the activity on their senses to the volunteers and described a positive relationship with the environment [55]. Some studies have shown that the possibility of conflict and social interaction while walking can reduce the stress-relieving effects. This potentially explains why the three physiological indicators in Group W did not significantly decrease in this experiment.

We analyzed behavioral differences across six emotional parameters. The results show that "engagement" and "excitement" were significantly lower in Group S than in Group W. In previous EEG studies, "engagement" was defined as directional attention and immersion or interest [56], and "excitement" was defined as high arousal [45]; thus, cognitive attention is higher when walking in a seasonal urban landscape forest than when sitting. This may be because walking provides more visual stimuli and changing landscape images. The emotional differences between the two groups are in contrast with the findings from a previous study [25], in which no significant difference in "engagement" or "excitement" were observed between walking and sitting in an urban green space. We found significant

differences in the emotional parameters between Group W and Group S. We believe that this may be related to the experimental environment and the "completely green" environment in the city. Some studies have reported significant seasonality results using quantitative brain wave data [35], and the seasonality of leaves plays an important role in the perception of, and physiological states induced by, forest landscape aesthetics [57]. We chose autumn due to the obvious seasonal environmental variation; the plant used (ginkgo) undergoes significant leaf color changes in the process of changing to yellow; thus, the landscape's spatial structure and color change. Volunteers in an environment with a high wavelength color (such as yellow) can experience more excitement [58]; thus, their brain functions are more active [59]. It follows that this explains the discrepancies in the findings of our study versus those of the aforementioned study.

In addition, in the study of spatial benefits, attention recovery theory (ART) emphasizes distance as a main component [60]. Group S occupied a relatively independent space without being disturbed, and Group W experienced a continuously changing space during walking. A stable and coherent space is conducive to attention recovery to obtain a sense of relaxation [25]; however, the boredom resulting from prolonged sitting can reduce spatial communication and relaxation. In our study, using a large area of yellow as the main landscape color is more likely to cause relaxation and vigilance [61]. This environment may trigger greater EEG sensitivity to emotion; thus, the "relaxation" emotional parameters in the walking group were significantly higher than those in the sitting group. In addition, the microscale landscape in the study was easy for participants to interact with [29], meaning that volunteers found it easy to observe and experience the surrounding environment. Volunteers in Group S were more willing to pay attention to a favorite part of the landscape in the experiment, which can explain the significantly higher "interest" emotional parameter of Group S versus Group W. Regarding the RAB index values, the two viewing behavior patterns showed significant differences in EEG channels AF3, F7, P7, FC5, FC6, F3 and T7. Because the decrease in RAB power induced by visual stimulation mainly occurred in the occipital lobe, and the decrease in RAB power induced by auditory stimulation mainly occurred in the parietal and temporal lobes, there was a negative correlation between the decrease in RAB ability and stimulus-specific information [40]. Our study revealed significant differences in the seven channels for the two behavioral patterns in the frontal, parietal, and temporal lobes but no differences in the occipital lobe. Hence, the information specificity of our experimental environment's characteristics is insufficient to induce different RAB index values between the two groups. We also found that the O2 channel of the occipital lobe and P8 channel of the parietal lobe showed significant differences in the absolute $\alpha$ wave values, and the FC6 and F4 channels of the frontal lobe showed significant differences in the absolute $\beta$ wave values. $\alpha$ waves indicate relaxation and $\beta$ waves are expressions of positive thinking and attention [62]. Because teenagers' brains are more susceptible to negative emotional stimuli and the $\beta$ wave is more dominant in the relaxed state, Group W obtained a higher level of relaxation and greater thinking ability. The occipital and parietal lobes were involved in activation. Zanzotto et al. [63] found that $\alpha$ and $\beta$ waves are most visible in the parietal and occipital lobes and are similar.

### *4.2. Psychological Index Influence*

There is a close relationship between GSB and psychological feedback. The results revealed significant differences in some psychological indicators of negative emotions between the two behavioral groups before and after the test. Group S and Group W demonstrated improved "tension-anxiety", while Group W showed improved "depression", "anger-hostility" and "self-esteem". We noticed that "vigor" (vitality and energy) increased significantly in Group W and was the only significant increase in the emotion index calculated from the self-report questionnaire. We speculate that this finding is related to the behavioral variables investigated by the research institute. The landscape stimuli that the experimenter is exposed to during walking and observing are more diverse than the relatively stable landscape observed while sitting. Some studies also show that the

elements of natural change can arouse a sense of wildness, and walking and watching in nature can enhance vitality [28]. This visual psychological effect has been found to occur after five seconds [30]. The continuously changing visual stimulus feedback significantly increased the "vigor" mood in Group W. In addition, the research results showed that walking significantly reduced negative moods in comparison with sitting, while there was no significant effect on positive moods. Numerous cross-sectional studies have proven the positive effects of entering green space and walking [55], such as a reduction in negative emotions and anxiety [53], to be consistent with the results of this study, which further confirmed the mental health benefits of walking. It is believed that walking outdoors in nature has a greater impact on vitality and more effectively reduces negative emotions than sitting.

### *4.3. Suggestions for Urban Landscape Forest Planning Based on Different Emotional Feedback*

The reduction in interaction time between humans and the natural environment has led to the need for effective green-space guidance to improve emotions [64]. The research results first further emphasize the impact of sitting and walking activities in seasonal landscape forests on the emotional health of adolescents. Our study showed that sitting in an autumn deciduous forest can help achieve better recovery, stress, and relaxation effects, manifesting as a significant decrease in systolic blood pressure and heart rate. Sitting in silence is more conducive than walking to generating "interest" emotions among adolescents. Understanding the promoting effect of spatial capacity building on human health [65], we can use landscape strategies to activate these conditions. First, the transformation of a space to provide environmental conditions and the reasonable use of different plant color combinations in landscape forests guide the generation of sitting, viewing, and staying behaviors, thereby achieving the goal of relaxation and interest activation. Studies have shown that golden plants trigger a warm and bright feeling in space [39], while red plants trigger high arousal [66]. These spatial landscape color combinations are used to increase landscape appeal and extend stay time.

The charm of forests lies in the unpredictability of the experiences they provide [67], especially the different landscape elements present during seasonal changes. These visual stimuli may induce users to engage in spontaneous activities, such as walking or sitting, and participants in the forest pay more attention to unique or interesting elements in the space [68]. In urban landscape forest planning, combinations of wild elements, such as berries, butterflies, and birds, are added. The creation of fish habitats enhances enjoyment of the area, and these naturally changing elements can also evoke a sense of wildness and friendliness [69], maximizing the benefits of biodiversity in the natural environment [70]. Second, abundant sitting facilities can be provided, including creating a quiet plant space and an appropriate number of recreational facilities, such as pavilions and chairs, to provide teenagers with a better interactive experience when observing the surrounding environment. According to the positive psychological and emotional feedback obtained from individuals engaging in the two behaviors in the autumn landscape forest environment in this study, the walking and viewing group showed a significant decrease in negative emotions and an increase in "vigor". We advocate the construction of trails in landscaped forests to maximize the comprehensive health benefits; additionally, the function of the trails should be improved to support multiple active travel purposes, such as walking and cycling [71], in order to stimulate positive emotions, such as user vitality. Simultaneously, the planning strategy of increasing entry and contact makes it easier for individuals to use the trail and connect with other green space areas and promotes the right to the fair use of nature.

## 5. Limitations

This study has several limitations. Firstly, our experimental environment was a real environment, and the emotional feedback results generated comprehensively reflect various sensory stimuli that may be particularly sensitive to emotions [72]. Emotional regulation

varies over time [6], and EEG analysis alone is insufficient to obtain an accurate explanation. Future studies should combine EEG with multiple indicators for a comprehensive analysis. Second, the multielement changes in natural environments are seasonal, and many studies have shown that the mechanism of environmental characteristics may be of great significance to the beneficial effects of bottom-up attention. Although selecting a pure forest path environment reduced interference, the differences in vegetation density, vegetation location [73], and vegetation composition [29] and structure [74] require further longitudinal analysis. In addition, we focused on only two behaviors in our sample of teenagers: sitting and walking. However, the findings cannot be generalized due to the small sample size. Moreover, the cross-sectional approach provides limited time observation feedback, and data were only collected from individuals in autumn landscape forests. In the future, in addition to expanding the sample size, it is necessary to consider cross-longitudinal experiments with multiseason comparisons, population age diversity, and behavioral variables, audiovisual environment variables [75] to promote research on outdoor spatial health activities. Finally, numerous studies have demonstrated the difference between typical urban spaces (such as commercial and square spaces) and green spaces in promoting health. This experiment only involves different behavioral pattern controls, and it is necessary to include urban environmental control samples for a more comprehensive empirical study.

## 6. Conclusions

Focusing on green space as a health intervention, this study obtained profound information about how different behaviors in seasonal green environments can promote adolescent emotional health. This study provides strategies and references for improving the spiritual and cultural effects of urban landscape forests through relevant guiding actions and plans for green space activities. According to the differences in the physiological and psychological indicators shown in the results, we believe that sitting in an urban forest can promote relaxation, recovery and calmness, and walking can promote "interest", and "vigor" and decrease negative emotions. We further analyzed 14 electrode channel $\alpha$ differences from $\beta$ waves and RAB indicators. The channel showed differences in the absolute $\alpha$ and absolute $\beta$ waves in the P8 electrodes in the parietal lobe, indicating the activation of spatial processing in the corresponding parietal lobe of the brain. The O2 channel of the occipital lobe and FC6 and F4 of the right frontal lobe $\alpha$ and $\beta$ waves showed significant differences. Group W obtained higher relaxation levels and thinking abilities than Group S. We suggest that urban environmental planning managers should use landscape strategies that activate corresponding behavioral conditions, paying attention to the guidance related to different behavioral patterns in the formed environment to achieve green spaces with better emotional impact. Considering the results of combining natural elements and different characteristics, recreational facilities and trails should be added to encourage natural viewing, participation, and interaction in scenic urban forests. Although the relationship between more diverse emotional needs and behavioral patterns in urban landscape forests remains to be explored, this study provides a research reference for urban green-space planners, namely, guidance related to behavioral patterns in green spaces, including the need for a focus on seasonal changes.

**Author Contributions:** Conceptualization, L.W.; methodology, L.W.; software, L.W.; validation, L.W.; formal analysis, L.W.; investigation, L.W. and S.L.; resources, L.W. and S.L.; data curation, L.W.; writing—original draft preparation, L.W. and Q.C.; writing—review and editing, Q.C., J.L., D.L., J.W. and S.L.; visualization, L.W.; supervision, L.W. and Q.C.; project administration, Q.C.; funding acquisition, L.W. and Q.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** Evidence-based studies on the spatiotemporal coupling mechanism of the ecological healthcare benefits of Bambusa emeiensis landscape forest (3227140499).

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. Xie, J.; Luo, S.; Furuya, K.; Sun, D. Urban Parks as Green Buffers during the COVID-19 Pandemic. *Sustainability* **2020**, *12*, 6751. [CrossRef]
2. Tsunetsugu, Y.; Lee, J.; Park, B.-J.; Tyrväinen, L.; Kagawa, T.; Miyazaki, Y. Physiological and psychological effects of viewing urban forest landscapes assessed by multiple measurements. *Landsc. Urban Plan.* **2013**, *113*, 90–93. [CrossRef]
3. Lyu, B.; Zeng, C.; Xie, S.; Li, D.; Lin, W.; Li, N.; Jiang, M.; Liu, S.; Chen, Q. Benefits of A Three-Day Bamboo Forest Therapy Session on the Psychophysiology and Immune System Responses of Male College Students. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4991. [CrossRef] [PubMed]
4. Peschardt, K.K.; Stigsdotter, U.K. Associations between park characteristics and perceived restorativeness of small public urban green spaces. *Landsc. Urban Plan.* **2013**, *112*, 26–39. [CrossRef]
5. Jiang, B.; Zhang, T.; Sullivan, W.C. Healthy Cities: Mechanisms and Research Questions Regarding the Impacts of Urban Green Landscapes on Public Health and Well-being. *Landsc. Archit. Front.* **2015**, *3*, 24–35.
6. Yang, M.; Deng, X.; An, S. The Immediate and Lasting Effect of Emotion Regulation in Adolescents: An ERP Study. *Int. J. Environ. Res. Public Health* **2021**, *18*, 10242. [CrossRef]
7. Restubog, S.L.D.; Ocampo, A.C.G.; Wang, L. Taking control amidst the chaos: Emotion regulation during the COVID-19 pandemic. *J. Vocat. Behav.* **2020**, *119*, 103440. [CrossRef]
8. Cracco, E.; Goossens, L.; Braet, C. Emotion regulation across childhood and adolescence: Evidence for a maladaptive shift in adolescence. *Eur. Child Adolesc. Psychiatry* **2017**, *26*, 909–921. [CrossRef]
9. McLaughlin, K.A.; Hatzenbuehler, M.L.; Mennin, D.S.; Nolen-Hoeksema, S. Emotion dysregulation and adolescent psychopathology: A prospective study. *Behav. Res. Ther.* **2011**, *49*, 544–554. [CrossRef]
10. Lennarz, H.K.; Hollenstein, T.; Lichtwarck-Aschoff, A.; Kuntsche, E.; Granic, I. Emotion regulation in action: Use, selection, and success of emotion regulation in adolescents' daily lives. *Int. J. Behav. Dev.* **2019**, *43*, 1–11. [CrossRef]
11. Espinosa, P.; De Meulder, B.; Ollero, A. River Restoration and Rehabilitation as a New Urban Design Strategy: Learning to Re-see Urban Rivers. *Int. J. Constr. Environ.* **2016**, *7*, 57–73. [CrossRef]
12. Wolch, J.R.; Byrne, J.; Newell, J.P. Urban green space, public health, and environmental justice: The challenge of making cities 'just green enough'. *Landsc. Urban Plan.* **2014**, *125*, 234–244. [CrossRef]
13. DuBose, J.; MacAllister, L.; Hadi, K.; Sakallaris, B. Exploring the Concept of Healing Spaces. *HERD Health Environ. Res. Des. J.* **2018**, *11*, 43–56. [CrossRef] [PubMed]
14. Velarde, M.; Fry, G.; Tveit, M. Health effects of viewing landscapes—Landscape types in environmental psychology. *Urban For. Urban Green.* **2007**, *6*, 199–212. [CrossRef]
15. Kim, S.; Park, H.; Choo, S. Effects of Changes to Architectural Elements on Human Relaxation-Arousal Responses: Based on VR and EEG. *Int. J. Environ. Res. Public Health* **2021**, *18*, 4305. [CrossRef] [PubMed]
16. Deng, L.; Luo, H.; Ma, J.; Huang, Z.; Sun, L.X.; Jiang, M.Y.; Zhu, C.Y.; Li, X. Effects of integration between visual stimuli and auditory stimuli on restorative potential and aesthetic preference in urban green spaces. *Urban For. Urban Green.* **2020**, *53*, 126702. [CrossRef]
17. Song, C.; Ikei, H.; Miyazaki, Y. Effects of forest-derived visual, auditory, and combined stimuli. *Urban For. Urban Green.* **2021**, *64*, 127253. [CrossRef]
18. Kuper, R. Here and Gone: The Visual Effects of Seasonal Changes in Plant and Vegetative Characteristics on Landscape Preference Criteria. *Landsc. J.* **2013**, *32*, 65–78. [CrossRef]
19. Zhao, J.; Xu, W.; Li, R. Visual preference of trees: The effects of tree attributes and seasons. *Urban For. Urban Green.* **2017**, *25*, 19–25. [CrossRef]
20. Paddle, E.; Gilliland, J. Orange Is the New Green: Exploring the Restorative Capacity of Seasonal Foliage in Schoolyard Trees. *Int. J. Environ. Res. Public Health* **2016**, *13*, 497. [CrossRef]
21. Giergiczny, M.; Czajkowski, M.; Żylicz, T.; Angelstam, P. Choice experiment assessment of public preferences for forest structural attributes. *Ecol. Econ.* **2015**, *119*, 8–23. [CrossRef]
22. Norouzi, N.; Fani, M. Comparison of weak and strong theories of environmental sustainability in the conceptual context of sustainable development. *Trends J. Sci. Res.* **2021**, *1*, 108–122. [CrossRef]
23. Dudek, T.; Marć, M.; Zabiegała, B. Chemical Composition of Atmospheric Air in Nemoral Scots Pine Forests and Submountainous Beech Forests: The Potential Region for the Introduction of Forest Therapy. *Int. J. Environ. Res. Public Health* **2022**, *19*, 15838. [CrossRef] [PubMed]
24. Wallner, P.; Kundi, M.; Arnberger, A.; Eder, R.; Allex, B.; Weitensfelder, L.; Hutter, H.-P. Reloading Pupils' Batteries: Impact of Green Spaces on Cognition and Wellbeing. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1205. [CrossRef] [PubMed]
25. Lin, W.; Chen, Q.; Jiang, M.; Tao, J.; Liu, Z.; Zhang, X.; Wu, L.; Xu, S.; Kang, Y.; Zeng, Q. Sitting or Walking? Analyzing the Neural Emotional Indicators of Urban Green Space Behavior with Mobile EEG. *J. Urban Health* **2020**, *97*, 191–203. [CrossRef]
26. Wei, H.; Hauer, R.J.; Guo, S. Daytime dynamic of spontaneous expressions of pedestrians in an urban forest park. *Urban For. Urban Green.* **2021**, *68*, 127326. [CrossRef]
27. Chang, W.-Y.; Lo, M.-T.; Huang, C.-F. The Influence of Emotional Environmental Pictures on Behavior Intentions: The Evidence of Neuroscience Technology. *Int. J. Environ. Res. Public Health* **2019**, *16*, 5142. [CrossRef] [PubMed]

28. Kobayashi, H.; Ikei, H.; Song, C.; Kagawa, T.; Miyazaki, Y. Comparing the impact of forest walking and forest viewing on psychological states. *Urban For. Urban Green.* **2020**, *57*, 126920. [CrossRef]
29. Wu, L.; Dong, Q.; Luo, S.; Jiang, W.; Hao, M.; Chen, Q. Effects of Spatial Elements of Urban Landscape Forests on the Restoration Potential and Preference of Adolescents. *Land* **2021**, *10*, 1349. [CrossRef]
30. Lin, W.; Chen, Q.; Zhang, X.; Tao, J.; Liu, Z.; Lyu, B.; Li, N.; Li, D.; Zeng, C. Effects of Different Bamboo Forest Spaces on Psychophysiological Stress and Spatial Scale Evaluation. *Forests* **2020**, *11*, 616. [CrossRef]
31. Yu, C.-P.; Hsieh, H. Beyond restorative benefits: Evaluating the effect of forest therapy on creativity. *Urban For. Urban Green.* **2020**, *51*, 126670. [CrossRef]
32. Janeczko, E.; Bielinis, E.; Wójcik, R.; Woźnicka, M.; Kędziora, W.; Łukowski, A.; Elsadek, M.; Szyc, K.; Janeczko, K. When Urban Environment Is Restorative: The Effect of Walking in Suburbs and Forests on Psychological and Physiological Relaxation of Young Polish Adults. *Forests* **2020**, *11*, 591. [CrossRef]
33. Hassan, A.; Tao, J.; Li, G.; Jiang, M.; Aii, L.; Jiang, Z.; Liu, Z.; Chen, Q. Effects of Walking in Bamboo Forest and City Environments on Brainwave Activity in Young Adults. *Evid.-Based Complement. Altern. Med.* **2018**, *2018*, 9653857. [CrossRef] [PubMed]
34. Mehdipanah, R.; Israel, B.A.; Richman, A.; Allen, A.; Rowe, Z.; Gamboa, C.; Schulz, A.J. Urban HEART Detroit: The Application of a Health Equity Assessment Tool. *J. Urban Health* **2021**, *98*, 146–157. [CrossRef] [PubMed]
35. Wang, Y.; Xu, M. Electroencephalogram Application for the Analysis of Stress Relief in the Seasonal Landscape. *Int. J. Environ. Res. Public Health* **2021**, *18*, 8522. [CrossRef] [PubMed]
36. Gerstenberg, T.; Baumeister, C.F.; Schraml, U.; Plieninger, T. Hot routes in urban forests: The impact of multiple landscape features on recreational use intensity. *Landsc. Urban Plan.* **2020**, *203*, 103888. [CrossRef]
37. Kuper, R. Preference and restorative potential for landscape models that depict diverse arrangements of defoliated, foliated, and evergreen plants. *Urban For. Urban Green.* **2020**, *48*, 126570. [CrossRef]
38. Paraskevopoulou, A.T.; Kamperi, E.; Demiris, N.; Economou, M.; Theleritis, C.; Kitsonas, M.; Papageorgiou, C. The impact of seasonal colour change in planting on patients with psychotic disorders using biosensors. *Urban For. Urban Green.* **2018**, *36*, 50–56. [CrossRef]
39. Guo, L.N.; Zhao, R.L.; Ren, A.H.; Niu, L.X.; Zhang, Y.L. Stress Recovery of Campus Street Trees as Visual Stimuli on Graduate Students in Autumn. *Int. J. Environ. Res. Public Health* **2019**, *17*, 148. [CrossRef]
40. Griffiths, B.J.; Mayhew, S.D.; Mullinger, K.J.; Jorge, J.; Charest, I.; Wimber, M.; Hanslmayr, S. Alpha/beta power decreases track the fidelity of stimulus-specific information. *eLife* **2019**, *8*, e49562. [CrossRef]
41. Zangeneh Soroush, M.; Maghooli, K.; Kamaledin Setarehdan, S.; Nasrabadi, A.M. A Review on EEG Signals Based Emotion Recognition. *Int. Clin. Neurosci. J.* **2018**, *4*, 118–129. [CrossRef]
42. Kim, Y.J.; Shin, D.J.; Kim, J.Y. A Study on the Characteristics on Brain Wave of Indoor Space Lighting by EEG Experiment. *J. Korean Inst. Spat. Des.* **2019**, *14*, 71–80.
43. Abraham, A.; Sommerhalder, K.; Abel, T. Landscape and well-being: A scoping study on the health-promoting impact of outdoor environments. *Int. J. Public Health* **2010**, *55*, 59–69. [CrossRef] [PubMed]
44. Li, H.; Zhang, X.; Bi, S.; Cao, Y.; Zhang, G. Psychological benefits of green exercise in wild or urban greenspaces: A meta-analysis of controlled trials. *Urban For. Urban Green.* **2022**, *68*, 127458. [CrossRef]
45. Neale, C.; Aspinall, P.; Roe, J.; Tilley, S.; Mavros, P.; Cinderby, S.; Coyne, R.; Thin, N.; Bennett, G.; Thompson, C.W. The Aging Urban Brain: Analyzing Outdoor Physical Activity Using the Emotiv Affectiv Suite in Older People. *J. Urban Health Bull. N. Y. Acad. Med.* **2017**, *94*, 869–880. [CrossRef]
46. Ochiai, H.; Ikei, H.; Song, C.; Kobayashi, M.; Miura, T.; Kagawa, T.; Li, Q.; Kumeda, S.; Imai, M.; Miyazaki, Y. Physiological and psychological effects of forest therapy on middle-aged males with high-normal blood pressure. *Int. J. Environ. Res. Public Health* **2015**, *12*, 2532–2542. [CrossRef]
47. Lee, M.S.; Lee, J.Y.; Park, B.J.; Miyazaki, Y. Interaction with indoor plants may reduce psychological and physiological stress by suppressing autonomic nervous system activity in young adults: A randomized crossover study. *J. Physiol. Anthropol.* **2015**, *34*, 21. [CrossRef]
48. Ramirez, R.; Palencia-Lefler, M.; Giraldo, S.; Vamvakousis, Z. Musical neurofeedback for treating depression in elderly people. Frontiers in Neuroscience. *Front. Neurosci.* **2015**, *9*, 354. [CrossRef]
49. McNair, D.M.; Lorr, M.; Droppleman, L.F.; EdITS. *Manual for the Profile of Mood States Manual (POMS)*; Educational and Industrial Testing Service: Princeton, NJ, USA, 1992.
50. Profile of Mood StatesForbes, E.E.; Dahl, R.E. Neural systems of positive affect: Relevance to understanding child and adolescent depression? *Dev. Psychopathol.* **2005**, *17*, 827–850.
51. Andersen, S.L.; Teicher, M.H. Stress, sensitive periods and maturational events in adolescent depression. *Trends Neurosci.* **2008**, *31*, 183–191. [CrossRef]
52. Sallis, J.F.; Owen, N.; Fisher, E. Ecological models of health behaviour. *Health Educ. Behav.* **2002**, *4*, 116.
53. Song, C.; Ikei, H.; Igarashi, M.; Takagaki, M.; Miyazaki, Y. Physiological and Psychological Effects of a Walk in Urban Parks in Fall. *Int. J. Environ. Res. Public Health* **2015**, *12*, 14216–14228. [CrossRef] [PubMed]
54. Ulrich, R.S.; Simons, R.F.; Losito, B.D.; Fiorito, E.; Miles, M.A.; Zelson, M. Stress recovery during exposure to natural and urban environments. *J. Environ. Psychol.* **1991**, *11*, 201–230. [CrossRef]

55. Li, H.; Dong, W.; Wang, Z.; Chen, N.; Wu, J.; Wang, G.; Jiang, T. Effect of a Virtual Reality-Based Restorative Environment on the Emotional and Cognitive Recovery of Individuals with Mild-to-Moderate Anxiety and Depression. *Int. J. Environ. Res. Public Health* **2021**, *18*, 9053. [CrossRef] [PubMed]
56. Aspinall, P.; Mavros, P.; Coyne, R.; Roe, J. The urban brain: Analysing outdoor physical activity with mobile EEG. *Br. J. Sport. Med.* **2015**, *49*, 272–276. [CrossRef] [PubMed]
57. Zhang, X.J.; Chen, J.; Li, Q.Y.; Liu, J.C.; Tao, J.P. Color quantification and evaluation of landscape aesthetic quality for autumn landscape forest based on visual characteristics in subalpine region of western Sichuan, China. *J. Appl. Ecol.* **2020**, *31*, 45–54.
58. Gotts, Z.M.; Ellis, J.G.; Deary, V.; Barclay, N.; Newton, J.L. The Association between Daytime Napping and Cognitive Functioning in Chronic Fatigue Syndrome. *PLoS ONE* **2015**, *10*, e0117136. [CrossRef]
59. Jang, H.S.; Kim, J.; Kim, K.S.; Pak, C.H. Human brain activity and emotional responses to plant color stimuli. *Color Res. Appl.* **2014**, *39*, 307–316. [CrossRef]
60. Kaplan, R.; Kaplan, S. *The Experience of Nature: A Psychological Perspective*; Cambridge University Press: Cambridge, UK, 1989; pp. 9–11.
61. Xie, J.; Liu, B.; Elsadek, M. How Can Flowers and Their Colors Promote Individuals' Physiological and Psychological States during the COVID-19 Lockdown? *Int. J. Environ. Res. Public Health* **2021**, *18*, 10258. [CrossRef]
62. Sanei, S.; Chambers, J.A. *EEG Signal Processing*; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2007; pp. 1–13.
63. Ramirez, R.; Vamvakousis, Z. Detecting Emotion from EEG Signals Using the Emotive Epoc Device. In Proceedings of the 2012 International Conference on Brain Informatics, Macau, China, 4–7 December 2012; Volume 7670, pp. 175–184.
64. Pergams, O.R.; Zaradic, P.A. Zaradic Evidence for a fundamental and pervasive shift away from nature-based recreation. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 2295–2300. [CrossRef] [PubMed]
65. Hartig, T.; Staats, H. The need for psychological restoration as a determinant of environmental preferences. *J. Environ. Psychol.* **2006**, *26*, 215–226. [CrossRef]
66. Elliot, A.J. A Historically Based Review of Empirical Work on Color and Psychological Functioning: Content, Methods, and Recommendations for Future Research. *Rev. Gen. Psychol.* **2019**, *23*, 177–200. [CrossRef]
67. Gao, Y.; Zhang, T.; Sasaki, K.; Uehara, M.; Jin, Y.; Qin, L. The spatial cognition of a forest landscape and its relationship with tourist viewing intention in different walking passage stages. *Urban For. Urban Green.* **2021**, *58*, 126975. [CrossRef]
68. Gao, Y.; Zhang, T.; Zhang, W.; Meng, H.; Zhang, Z. Research on visual behavior characteristics and cognitive evaluation of different types of forest landscape spaces. *Urban For. Urban Green.* **2020**, *54*, 126788. [CrossRef]
69. Zhang, H.; Chen, B.; Sun, Z.; Bao, Z. Landscape perception and recreation needs in urban green space in Fuyang, Hangzhou, China. *Urban For. Urban Green.* **2013**, *12*, 44–52. [CrossRef]
70. Kexiu, L.; Elsadek, M.; Liu, B.; Fujii, E. Foliage colors improve relaxation and emotional status of university students from different countries. *Heliyon* **2021**, *7*, e06131. [CrossRef]
71. He, D.; Lu, Y.; Xie, B.; Helbich, M. Large-scale greenway intervention promotes walking behaviors: A natural experiment in China. *Transp. Res. Part D Transp. Environ.* **2021**, *101*, 103095. [CrossRef]
72. Li, Z.; Kang, J. Sensitivity analysis of changes in human physiological indicators observed in soundscapes. *Landsc. Urban Plan.* **2019**, *190*, 103593. [CrossRef]
73. Kabisch, N.; Püffel, C.; Masztalerz, O.; Hemmerling, J.; Kraemer, R. Physiological and psychological effects of visits to different urban green and street environments in older people: A field experiment in a dense inner-city area. *Landsc. Urban Plan.* **2020**, *207*, 103998. [CrossRef]
74. Hong, X.-C.; Cheng, S.; Liu, J.; Dang, E.; Wang, J.-B.; Cheng, Y. The Physiological Restorative Role of Soundscape in Different Forest Structures. *Forests* **2022**, *13*, 1920. [CrossRef]
75. Chen, Z.; Zhu, T.-Y.; Liu, J.; Hong, X.-C. Before Becoming a World Heritage: Spatiotemporal Dynamics and Spatial Dependency of the Soundscapes in Kulangsu Scenic Area, China. *Forests* **2022**, *3*, 1526. [CrossRef]


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

buildings

MDPI

*Article*

# Improving the Indoor Environment through an Indoor Green Curtain System

**Ghulam Qadir [1,*], Niranjika Wijesooriya [2], Arianna Brambilla [2] and Fernando Alonso-Marroquin [1]**

[1] School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia; fernando.alonso@sydney.edu.au
[2] School of Architecture, Design and Planning, The University of Sydney, Sydney, NSW 2006, Australia; arianna.brambilla@sydney.edu.au (A.B.)
* Correspondence: ghulam.qadir@sydney.edu.au

**Abstract:** People are spending more and more of their lives indoors, making thermal comfort and air quality essential factors for their health and well-being. The use of natural elements within indoor spaces can improve the indoor environment and air quality, but can also bring multiple health and well-being, psychological, cognitive, and behavioral benefits due to its biophilic effect. Indoor vertical greenery strategy in buildings can give these benefits to the building occupants. In this study, a prototype of a living green curtain is assessed to evaluate the benefits that may derive when used as a shading device. The analysis evaluated the performance of the green curtain prototype compared to the other two scenarios, no curtains (control module) and external blind. Temperature, relative humidity, air quality, and solar radiation were measured in the indoor environment. Results indicate that the green curtain module was cooler by 0–4 °C than the control module during the peak solar radiation hours, and the difference even reached up to 8 °C on hotter days. Due to the evapotranspiration effect, the green curtain recorded the highest daily average relative humidity of 67%. This study demonstrates the potential ability of a green curtain to improve air quality and thermal comfort.

**Keywords:** greening system; air quality; thermal comfort; green buildings; indoor environmental quality; prototype; biophilic design; biophilia

**Citation:** Qadir, G.; Wijesooriya, N.; Brambilla, A.; Alonso-Marroquin, F. Improving the Indoor Environment through an Indoor Green Curtain System. *Buildings* **2023**, *13*, 1307. https://doi.org/10.3390/buildings13051307

Academic Editors: Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Bao-Jie He and Shi Cheng

Received: 9 April 2023
Revised: 10 May 2023
Accepted: 15 May 2023
Published: 17 May 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

The rapid increase in urbanization has created several environmental issues, including the urban heat island effect [1], increased air pollution [2], increased temperature [3], and depletion of resources [4,5]. These negative effects add to climate change. In the urban environment, the high building density consumes more resources as the building sector accounts for 40% of the world's energy usage [6], mainly due to the high conditioning energy loads. Heating, ventilating, and air conditioning (HVAC) systems consume approximately 50–70% of the building energy, primarily because of inefficient building service systems and poorly insulated external walls [7]. The other reason for this high consumption lies in the control strategy, which was identified as a parameter that has a high potential to affect energy efficiency [8]. Therefore, reducing energy demand for heating and cooling is essential for improving the energy efficiency of a building, but modern technology re-circulates the air instead of refreshing it, which leads to reduced air quality [9]. Inadequate ventilation results in poor indoor air quality (IAQ) [10]. IAQ represents attributes of the respirable air inside a building (indoor climate), including gaseous composition, humidity, temperature, and contaminants [11]. With people spending 90% of their time inside buildings [12], IAQ is an essential factor contributing to people's health, comfort, and well-being. Indeed, poor IAQ can result in lower productivity and dissatisfaction in the workplace [13]. On the contrary, better IAQ can enhance the lives of building occupants, increase the resale value of the building, and reduce liability for building owners [14].

Recently, extreme events (e.g., bushfires and the COVID-19 pandemic) are forcing people to spend even more time indoors and persuading the building operation strategies to isolate the indoor environment. In addition, to keep the indoor environment healthy, the implementation of biophilic design strategies is important [15], because, during the building life cycle, the emissions of carbon dioxide is more than in the construction phase [16] and a biophilic design can minimize these emissions. The biophilic design uses natural elements on the premise to enhance human–nature connectedness which could immensely contribute towards health and well-being. The use of natural elements providing biophilic visual connections inside the building can improve IAQ as a factor of indoor environmental quality (IEQ) [17], as IEQ is defined by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) [18] as "a perceived indoor experience of the building's indoor environment that includes aspects of design, analysis, and operation of energy-efficient, healthy and comfortable buildings". Consistently occupying spaces with natural elements can have positive effects on mood and cognitive performance [19], low pulse rates [20], and psychological nervousness (mental stress) [21], and it can also slow down blood flow, which minimizes the burden on the heart and, potentially preventing cardiovascular and cerebrovascular diseases [21]. Green plants also have a soothing effect on the human mind causing relaxation of the nervous system, reduction of mental stress, and fatigue prevention [22].

In recent decades, different internal and external vertical greening systems have spread worldwide. There are several terms used to define and describe vegetated vertical surfaces or green surfaces in buildings. Wall vegetation primarily refers to free-standing walls, and dividing properties [23]. Green or greened facades commonly feature woody or herbaceous climbers either planted into the ground or in planter boxes to cover buildings with vegetation, as this practice has been seen in many developed cities globally [24]. Green curtains and green facades have been used interchangeably in research studies. To create a green curtain, hanging shrubs are planted around the building as part of the facade [25]. Panels or geotextile felts are used to make living walls, either pre-cultivated or fixed to vertical supports or on the wall structure itself [25,26].

Vertical greenery systems have shown their advantages in different climates, as green walls improve the thermal comfort of indoor environments, and can also reduce a building's energy consumption during the summer and winter seasons [27–30]. Moreover, the cooling load was reduced by 20% when plants were used as green walls instead of blinds under the same solar radiation intensities [31]. In comparison to the concrete wall, Cheng [32] found that green walls can reduce indoor temperature and delay the heat transfer from outdoor to indoors, while, in comparison to bare walls, green walls lead to a 6.1 °C and 4 °C reduction in external wall temperature on sunny and cloudy days, respectively [33]. Some other studies about the benefits and uses of green walls were conducted in different climates: Mediterranean [34], Mediterranean continental [25], hot and dry Middle Eastern [35], humid subtropical [36], temperate [37], temperate oceanic [33], tropical [32], subtropical [28], and maritime [31]. Overall, greenery systems can reduce the wall and roof surface temperature, resulting in a reduction in heat transfer through building envelopes, which can be as high as 80–90% [38]. Moreover, the external vertical greening fully uses the building's structural surfaces, such as facades, roofs, windows, columns, and balconies, to grow green plants. The external vertical greenery systems in buildings can address problems such as the lack of biodiversity [39], urban drainage pressures [40], improving indoor thermal environmental conditions, and reducing cooling load [41,42]. It is clear from these studies that the vertical greening effect on a building can vary based on climates, plant species, and other factors.

Recent studies on the uses of vertical greening systems mostly focus on green walls and green roofs, the former having greater potential considering that the extent of the facade greening area can double the ground footprint of buildings in urban centers [43,44]. Indoor green walls or vertical greening systems in the form of indoor living walls, and vertical greening systems can affect the room's relative humidity, as shown by [45], who

monitored relative humidity and found that, near the living wall, higher relative humidity levels were experienced, increasing the overall relative humidity by 15%. This additional indoor relative humidity was identified as a potential criticality of living walls, as it may cause respiratory problems [46]. In Athens, Greece, an investigation of the absolute relative humidity of an area shaded by a deciduous tree and an unshaded area was undertaken [47]. It was found that the relative humidity measured in the shaded area was constantly higher than the unshaded area, clearly showing the effects of evaporated water from the trees. In dry environments, high relative humidity may be favorable; however, in already humid climates, this may cause discomfort [48]. Monitoring relative humidity and implementing a ventilation system may aid in achieving more comfort for occupants [45]. The main factors that influence energy usage and climate are: vegetation quality and quantity, leaf area index, vegetation species, substrate properties, air ventilation/infiltration rate of the building, façade properties, location and orientation of the building, and vegetation and local climate [48]. Other forms of indoor greening can be integrating plants as additional insulation layers. Another beneficial effect of indoor vertical greening is IAQ. Studies have found that indoor vertical greening systems can prove IAQ [49,50] by decreasing carbon dioxide concentration [50] and can ultimately lead to fewer medical issues arising from poor IAQ [51].

Mostly outdoor vertical greening systems have been discussed in literature focusing on issues such as the insulating effects of plants on facades (mostly outdoor), plants' evaporative cooling effects, and habitat creation for urban wildlife. This particular research work focuses on passive low-tech windows with an indoor vertical greening system used as internal shading devices to capture solar energy, redistribute natural light, and create psychological comfort for the inhabitants. This study aims to monitor a prototype for an indoor green curtain. The objective is to assess the potential of this shading typology as a means to improve thermal comfort and the IAQ in residential applications for warm temperate climates. The assessment relies on a performance comparison of thermal comfort parameters (air temperature and relative humidity) and air quality. The thermal comfort parameters are compared between three modules: the prototype, a base case without any shading device, and an external window blind module. The air quality is only compared between the prototype module and base case without any shading device.

## 2. Methodology

The methodology consists of first designing and then constructing three modules: the No Curtain (NC) module, the Green Curtain (GC) module, and the Window Blind (WB) module, as shown in Figure 1. The first module, NC was used as a control or reference. Indeed, the window was cleaned and kept without any shading system. This module acted as room area in a house that receives maximum sunlight and heats at a higher rate than other areas. The GC was the second module which was set up on a wooden counter in front of a glass window panel. The third module accommodated an external blind to fully shade the window from the outside. All three modules were separated by plywood walls, in the form of plywood box frames with a plexiglass sheet opposite to the window frames from the inside to enclose the modules in the form of a room environment, shown in Figure 1. This allowed the indoor environment of the different modules to be compared, and it showed whether GC had been effective in improving thermal comfort and air quality inside the module environments. Sensors were set up on the surfaces of the module ceilings to monitor the thermal comfort parameters and air quality. A customized sensor was built to monitor the indoor solar radiation intensity coming from outside.

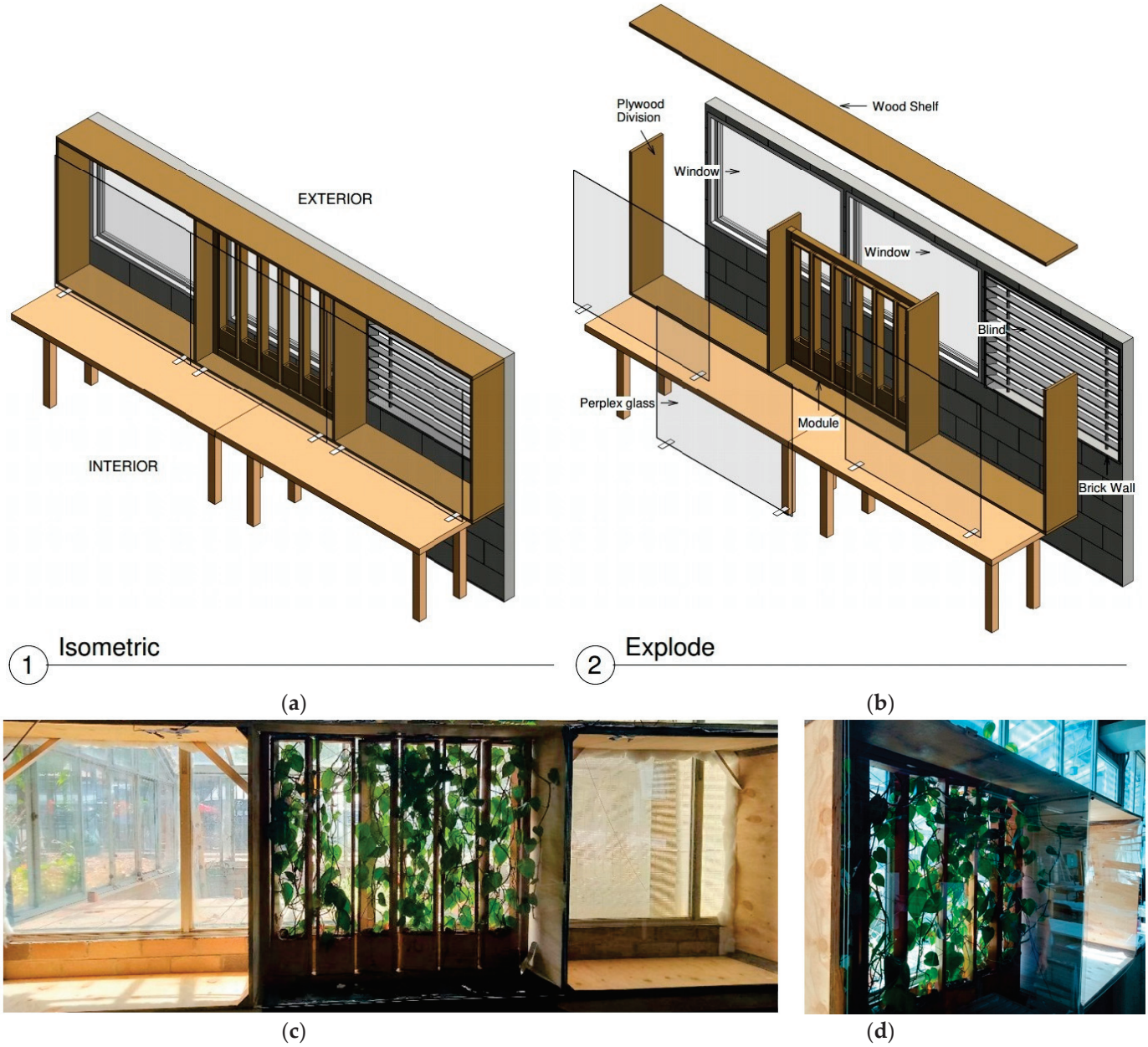



**Figure 1.** (**a**) Isometric modeled image of the experimental set-up showing all the components, and exterior and interior environment. (**b**) Exploded view of the components of the experimental set-up. The model was designed and drafted in Autodesk Revit. (**c**) Experimental set-up showing three modules (NC, GC, and WB). Each section of the GC can be vertically rotated. The fully grown Philodendron cordatum plant is included on each section of the GC module. The hemp mesh running from top to bottom provided a climbing medium for the plant. (**d**) A 3D view of the plexiglass sheets in front of the modules. The external side of the modules is the glasshouse mimicking the Australian outback region climate. Detailed dimensions of the GC prototype and the experimental setup are shown in Appendix A (Figures A1 and A2).

### *2.1. Location and Climatic Conditions*

The experimental site is located in Sydney, in the eastern part of New South Wales State, at 33.8688° S latitude and 151.2093° E longitude. Sydney has a warm temperate climate with four distinct seasons, shifting from mild and cool in the winter to warm and hot in the summer, with no extreme seasonal differences, as the weather is moderated by proximity to the ocean.

### *2.2. Experimental Set-up*

The modules and the green curtain prototype were placed in an interior environment as shown in Figure 1a. The individual components in the experiment as modeled image are shown in Figure 1b. The exterior environment of the modules was a glasshouse. This choice allowed us to test the benefit of the green curtain in indoor module (room) conditions. Indeed, the glasshouse was not equipped with any shading system, and thus the indoor temperatures are usually higher than the ones normally found in residential buildings. The temperature in the glasshouse varied considerably, which ideally resembled the extreme climatic conditions of the Australian outback region; e.g., 50 °C temperature has also been recorded in the summer season. Therefore, the temperature in the controlled climate of the glasshouse was higher than the normal Sydney ambient temperature.

#### 2.2.1. Design and Working Mechanism of Green Curtain Prototype

The entire curtain frame (Figure 1c,d) was made of commercial cedar also known as Western Red Cedar, treated to be water-resistant with natural sealants, such as Tung oil. The treatment included three to four coating layers of Tung oil, applied in 10 days. This sealant was chosen due to its environmental benefits; indeed, it is both biodegradable and renewable, making it an ideal material for this project [52]. Pivot hinges were used to hinge the panels from top and bottom. Indeed, the curtain is designed with a certain degree of flexibility, allowing the panels to rotate to either shade, and filter or allow sunlight in the room, according to the season's demand. The prototype is operated manually, and each panel can rotate 360°. This flexibility provides a higher degree of control to the occupants, which is proven to be beneficial in buildings [53]. A wooden ply box was made in the lower section of the panel (Figure 1c); it contains the soil and the plant in jute bags. For the connection between the parts of the prototype to support the plant's growth in an upward direction, an aluminum mesh was mounted, running from top to bottom. Plants took approximately three months to grow and climb the structure. For irrigation purposes, a pipe of 0.2 mm in diameter was provided at the bottom of the box to allow for the outflow of the water.

#### 2.2.2. Plant Specie

For this experiment, Philodendron cordatum was chosen as the crawling plant (Figure 1c) due to its low maintenance cost. The Philodendron cordatum plant, also known as the Heart Leaf plant, is commonly used indoors, and it is renowned for its air-purifying qualities [54] by removing formaldehyde from the air. Moreover, it is a relatively tough plant, which makes it suitable for high-temperature applications. Soluble, all-purpose plant food was mixed with water and given to the plants weekly for faster growth, providing the plants with extra nutrients. The plants were placed in rectangular hessian bags before placing them in the panels. The bags were filled with peat moss. There was no irrigation system installed, and the plants were watered manually. Watering was carried out twice a week with a cup of water each time for each plant.

Hessian material was preferred for the plant bags because it is solely made from fibers of jute plants, making it fully biodegradable and organic. It is recyclable and reusable, making it an eco-friendly material and a sustainable alternative to plastic planter boxes. Compared to terracotta, the hessian fabric is lightweight yet durable, strong, and resilient, allowing the prototype to be easily portable and avoid adding any unnecessary extra weight.

#### 2.2.3. Data Arrangements

The prototype was equipped with multiple sensors to detect air temperature, relative humidity, air quality, and solar radiation. The specifications of all the sensors are shown in Table 1. The air temperature and relative humidity sensors were placed just below the ceiling inside each module to allow for performance comparison. Figure 2 shows the location of the sensors. The solar radiation sensors were only used for the GC module

placed on both sides of the window glass near the ceiling, measuring the outside solar radiation intensity ($q^r_{out}$), and the radiation on the inner side of the window before the prototype, respectively, in W/m$^2$. It was noticed that there was negligible difference between the two, as the radiation on the inner side of the window was only 8% less than outside because the glass was highly transparent. Therefore, the radiation outside solar radiation was considered as the primary solar radiation value. The air quality sensors were only used for GC and WB modules measuring the quality of indoor air in µg/m$^3$. A preliminary test to compare the air quality of NC and WB was carried out for 48 h period where two sensors were arranged for the experiment. The results were monitored online, and it was found that the values in the two modules did not differ from each other. This result was expected since the primary factor of variation of air quality is the presence of plants in the GC module. Therefore, based on those 48 h data, we decided to install the air quality sensors only in GC and WB. Moreover, for comparison with GC, only one module was required as base case.

**Table 1.** Sensors and data-measuring period of the parameters.

| Parameters | Duration of Measurement | Sensor | Measurement Range | Accuracy |
|---|---|---|---|---|
| Air temperature (°C) and relative humidity (%) | 4 November 2021–22 March 2022 | HOBO MX2302A | 40–70 °C<br>0–100% | ±0.2 °C<br>±2.5% |
| Solar radiation intensity (W/m$^2$) | 15 December 2021–22 March 2022 | Solar Jinie | 0–1200 W/m$^2$ | ±20 W/m$^2$ |
| Air quality (µg/m$^3$) | 1 March 2022–21 March 2022 | PM 2.5 Wireless Indoor,<br>PM 2.5 Wireless Outdoor | 0–999 µg/m$^3$ | ±15 µg/m$^3$ |

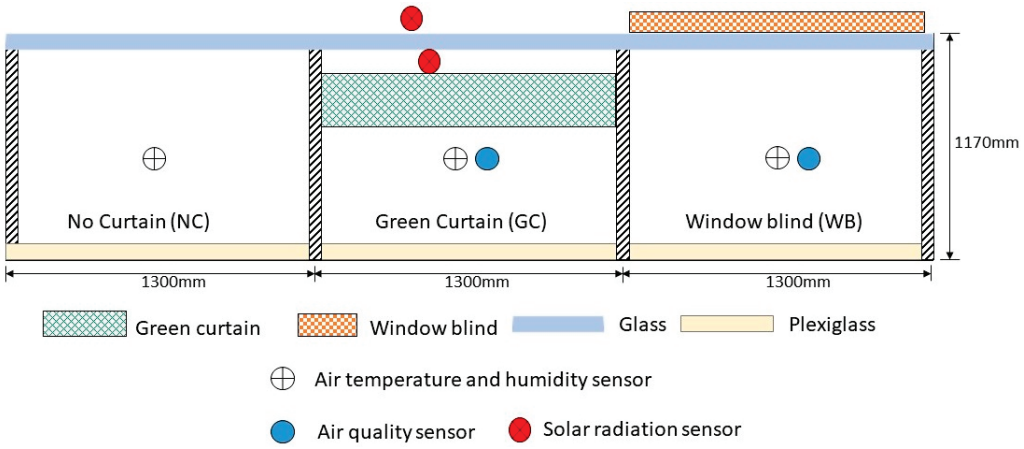



**Figure 2.** Experimental set-up showing three modules (NC, GC, and WB) and locations of all the sensors.

The air quality sensor was not installed in NC module because, during a litmus test before the actual measurement, it was noticed that the difference may not be a significant one. The sensor's specifications are shown in Table 1. Data gaps were fixed with linear interpolation.

## 3. Solar and Heat Energy Flow

The mechanisms of thermal transfer in the GC are convection (heat transport due to fluid motion), conduction (heat transfer due to molecular vibrations in a solid), and solar radiation (heat transport by photons). Part of the solar radiation is converted into heat and a part is biochemically stored by photosynthesis, and the remainder of the solar energy transmits through the plexiglass sheet. Part of the thermal energy is absorbed by the plants via evapotranspiration. The remaining thermal energy passes through the plexiglass sheet.

The heat flowing inside the building consists of an incoming solar radiation and a heat convection:

$$q_{Total} = q^r_{in} + q_{in} \quad (1)$$

where:

$q_{Total}$ is the total energy;
$q_{in}$ is the heat flowing by convective heat transfer;
$q_{in}^{r}$ is the solar energy that passes through the plexiglass sheet (the last material layer in the GC module), which is given as

$$q_{in}^{r} = q_{out}^{r} - q_r - q_{ph} - q_h \quad (2)$$

where:

$q_{out}^{r}$ is the incoming solar energy outside the GC module;
$q_r$ is the solar energy reflected by the GC;
$q_h$ is the solar energy converted into heat inside the GC module;
$q_{ph}$ is the solar energy used by plant leaves for photosynthesis by the chemical reaction below [55]:

$$6CO_2 + 6H_2O \overset{q_{ph}}{\rightarrow} C_6H_{12}O_6 + 6O_2 \quad (3)$$

Photosynthesis absorbs only a part of the solar spectrum, usually around the 400–700 nm waveband that ranges from violet to red. Overall, the efficiency of photosynthesis varies depending on the specific plant species and environmental conditions, but it is generally in the range of 3–6% [56], and the percentage of absorption depends on many factors [57]. During photosynthesis, energy can be lost as heat due to the high temperature of the chloroplasts in which the process occurs. Additionally, energy can be lost through the dissipation of excess light energy, which can cause damage to the leaves. The radiation, $q_h$, accounts for all processes where the radiation is converted into heat. The reflection of solar energy by plants, $q_r$, is related to the albedo effect [58]. Albedo is a measure of the reflectivity of a surface, or the fraction of incident solar radiation that is reflected by the surface [59]. It is estimated that the reflectance of plants ranges from about 5% to 30%, depending on the wavelength of the incident radiation and the specific plant species [60].

Apart from radiation, we need to account for the heat flow through the GC module by convection and conduction in the various layers of materials of the module. It is assumed that the temperature variation on the GC is slow enough so that there is no accumulation of thermal energy by the thermal mass of the materials. The thermal gradient is calculated by $\Delta T = \frac{q}{R}$ in each solid phase, and $\Delta T = \frac{q}{h}$ in each gaseous phase. Here, R [$Cm^2/W$] is the R-value of the GC component and $h$ [$W/(Cm^2)$] is the heat convection coefficient of the air. A special zone is the area occupied by the leaves. Here, there is a heat absorption $Q$ [$W/m^3$] due to the combined effect of the evapotranspiration [61] and the fraction of solar radiation converted into heat.

$$Q = -Q_{et} + \frac{q_h}{D} \quad (4)$$

where:

$Q_{et}$ [$W/m^3$] is the energy lost by evapotranspiration in the GC module;
$q_h$ [$W/m^2$] is the solar energy converted into heat, also called solar irradiance;
$D$ [m] is the thicknes of the folliage, $D = x_2 - x_1$.

The amount of energy required to evaporate water depends on several factors, including the initial temperature of the water, the atmospheric pressure, and the humidity of the air [62,63]. However, on average, it takes about 2257 kilojoules (kJ) of energy to evaporate one liter of water at room temperature and at standard atmospheric pressure [64]. This energy is used to overcome the intermolecular forces that hold the water molecules together, allowing them to break free and enter the gaseous phase. The power required to evaporate one liter of water in a day can be calculated as Power = Energy/Time = 2257 kJ/24 h = 94 W. Taking into account the fact that the average incoming solar radiation in the GC module is 50 $W/m^2$ × 1.3 m × 1.1 m = 70 W and the average amount of water added to the GC plant

is half a liter per day, the evapotranspiration ($ET$) will make a significant contribution to the energy budget.

The temperature profile in the folliage is calculated by the steady state heat equation

$$\frac{\mathrm{d}^2T}{\mathrm{d}x^2} = \frac{Q}{DR_{eff}} \tag{5}$$

where $R_{eff}$ is the effective R-value of the foliage and $D$ is the thickness of the foliage. Solving this equation leaves the parabolic temperature profile as shown in Figure 3. The integration constants can be solved using the heat fluxes as boundary conditions, i.e., temperature and heat fluxes are continuous at the boundaries.

$$T_{out} - T(x_1) = (\frac{1}{h_{out}} + \frac{1}{R_{glass}})q_{out} \tag{6}$$

where:

$T_{out}$ is the outdoor temperature;
$h_{out}$ is the convective heat transfer in the outside environment;
$R_{glass}$ is the $R$-value of the window glass.

The boundary condition at the point $x_2$ is given by

$$T(x_2) - T_{in} = (\frac{1}{h_{in}} + \frac{1}{R_{plexi}})q_{in} \tag{7}$$

where:

$T_{in}$ is the indoor temperature;
$h_{in}$ is the convective heat transfer in the inside environment after the plexiglass sheet;
$R_{plexi}$ is the R-value of the plexi glass.

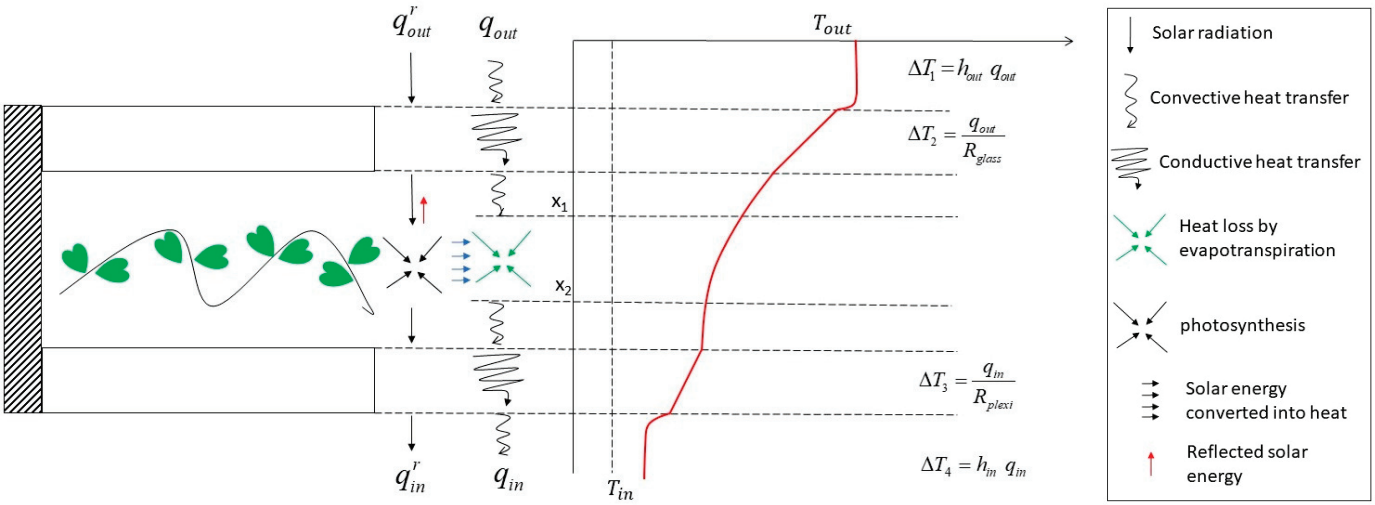



**Figure 3.** The mechanism of thermal transfer and heat absorption in the GC module. A part of the incoming solar radiation $q_{out}$ [W/m$^2$] is absorbed by photosynthesis $q_{ph}$ [W/m$^2$] (black arrows) and heat $q_h$ [W/m$^2$] (blue arrows), and a part is reflected $q_r$ [W/m$^2$] (red arrow). The remaining $q_{in}$ enters the building. In addition, the interior heat flow $q_{in}$ [W/m$^2$] is different than the exterior heat flow $q_{out}$ [W/m$^2$] due to the amount of heat loss by evapotranspiration and the solar radiation converted into heat. The temperature profile is constructed based on the hypothesis of quasi-static equilibrium, and the temperature gradients are calculated based on thermal material parameters.

The governing equations show that the main effect of the evapotranspiration in the GC is to produce a drop of the heat flow indoors, $q_{in} = q_{out} - q_{et} + q_h$. In addition, the GC reduces the amount of solar radiation $q^r_{in} = q^r_{out} - q_r - q_{ph} - q_h$, allowing a comfortable

natural lighting indoors. Without CG, the indoor heat flow will be raised due to lack of evapotranspiration and the increase of indoor solar radiation. The main effect of the external blind is to drastically reduce the incoming solar radiation $q_{out}$, with a detrimental effect to the indoor natural illumination and creating discomfort for the indoor occupants.

## 4. Results and Analysis

The results are discussed in four sections. The first section discusses the ambient conditions in which the experiment was performed. The second section analyzes the solar radiation intensity and the air temperature during solar radiation hours. The third section then discusses the complete recorded temperature and relative humidity data (during solar and non-solar radiation hours). The last section discusses air quality. The temperature and relative humidity results are shown in the form of seasons: November was late spring, December was early summer, January was mid-summer, and February and March were late summer and early autumn, respectively.

### *4.1. Ambient Conditions*

The experiment started in November 2021. It was the sixth wettest year on record, with 2021 rainfall being 30% above average. Sydney had its wettest November since national records began in 1900 [65]. It was not a hot summer. The external ambient mean hourly values with error bars of the outdoor temperature and relative humidity are shown in Figure 4.

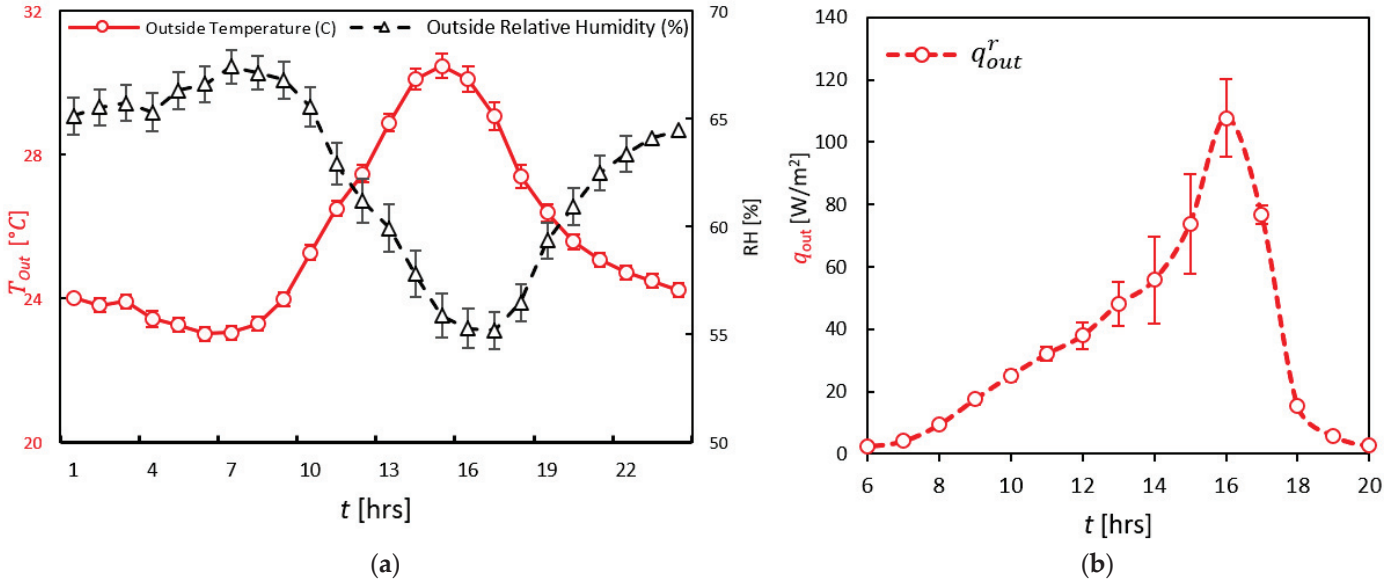



**Figure 4.** (**a**) Mean hourly outdoor temperature and relative humidity (with error bars) recorded during the experimental period (4 November 2021–21 March 2022). (**b**) Mean hourly solar radiation intensity (with error bars) in solar radiation hours recorded during the experimental period (8 October 2021–21 March 2022).

During the study period, the highest recorded temperature was 46.9 °C, with solar radiation hours ranging from 12 to 15. The study commenced in the spring of 2021 and concluded in the autumn of 2022. The observation period was 5 months (November, December, January, February, and March). During the experiment, the maximum temperatures were recorded around 15:00 hrs–16:00 hrs, while the minimum temperature was noticed in the early morning hours before the sunrise.

### *4.2. Solar Radiation and Air Temperature*

The two external factors which had a high impact on the environment of the modules were the solar radiation ($q^r_{out}$) and the oudoor temperature $T_{out}$. As an example, the 1 February

data of solar radiation and temperatures are shown in Figure 5a,b, respectively. The raw data of every day for solar radiation and temperature are shown in the Supplementary Material. The daily solar radiation ranged up to 455 W/m$^2$ during the experiment. The mean value of solar radiation recorded was 38 W/m$^2$, though it kept increasing as the experiment moved into late summer (February) and early autumn (March). Due to the wet early and mid-summer, the solar radiation values were low because of a high proportion of diffuse radiation [66]. However, in late summer and early autumn, the intensity of solar radiation increased as the weather became clearer. The solar radiation was directly impacting the outdoor temperature, which was then affecting the temperature of the modules inside.

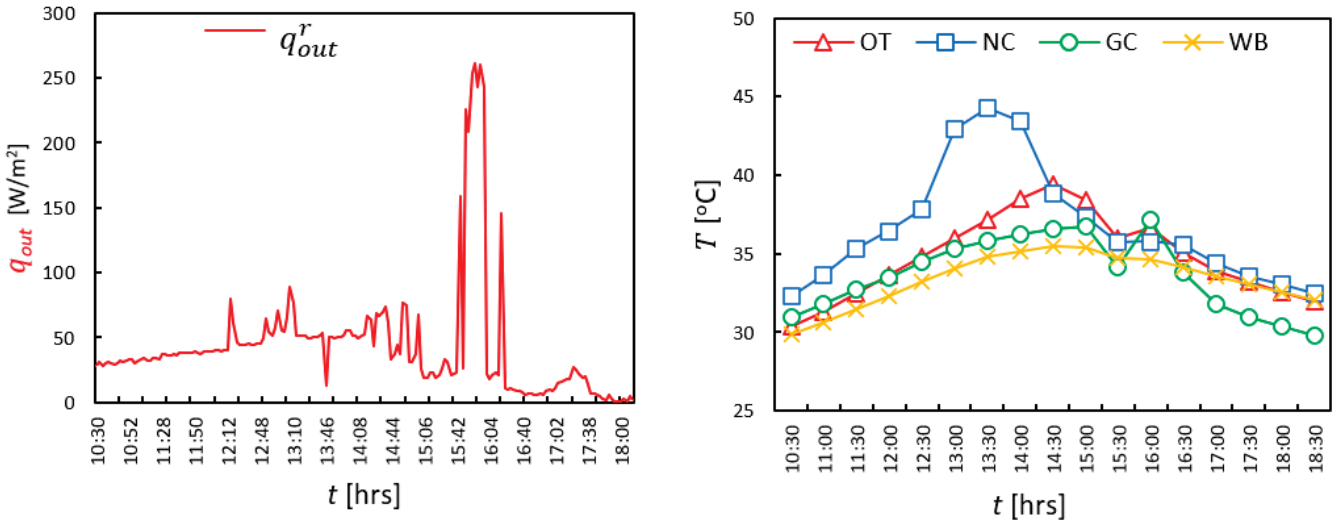



**Figure 5.** A typical presentation of the daily solar radiation and temperature measurements recorded during the experiment. (**a**) Solar radiation intensity recorded on 1 February 2022 externally. The data were recorded after every 2 min. (**b**) Temperature data of 1 February 2022 for the outdoor environment, and the inside of the three modules (NC, GC, and WB). The pattern shows three time frames: before the peak hours (10:30–12:30 hrs), at the peak hours (12:30–14:00 hrs), and after the peak hours (14:30–18:00 hrs). The time frames change on daily basis based on the solar angle.

Figure 5b shows the temperature recorded for every 30 min on 1 February during the solar radiation hours. The outdoor temperature is directly correlated to the solar radiation; e.g., from 18 January–22 January, 90% of the values of solar radiation were below 100 W/m$^2$ and the mean outdoor temperature during that period was 27 °C, which is 3 °C less than its mean temperature (30 °C) during January. It is important to note that Figure 6 shows a pattern of three different time frames: (i) the rise towards the peak temperature; (ii) the peak temperature hours; and (iii) the fall of temperature after the peak has passed. The peak hours graph kept on changing monthly; e.g., in November, the peak hours were between 13:30–15:00 hrs, in December 13:00–16:30 hrs, January 13:00–16:30 hrs, February 12:30–15:30 hrs, and March 12:00–15:00 hrs. High-temperature peaks were noticed in the NC module from late spring (November) to late summer (February). The primary peak (27.5 °C) occurred around 15:00 hrs in late spring (November) and slightly late in early summer (December) at 16:00 hrs (31 °C). However, a secondary peak (30 °C) was also noticed in early summer at around 13:30 hrs. In the mid-summer (January), two primary peaks were noticed at 13:30 hrs and 16:30 hrs, with temperatures of 33.5 °C each, respectively. During the peak hours, the GC always had a minimum value compared to the NC and was the quickest to cool when the peak was passed. It was primarily because of the evapotranspiration effect of the plants [67] in the GC module. This cooling-down effect after peak hours was also noticed in other studies [45,49,68]. The main reason that the peaks were found in the NC module the most was the entrapped heat being generated due

to the greenhouse effect [69]. As the WB was blocking most of the solar radiation, therefore, understandably, it had the minimum indoor temperature before and during the peak hours. However, due to some radiation still penetrating through the blinds, the entrapped heat inside the WB module increased the temperature.

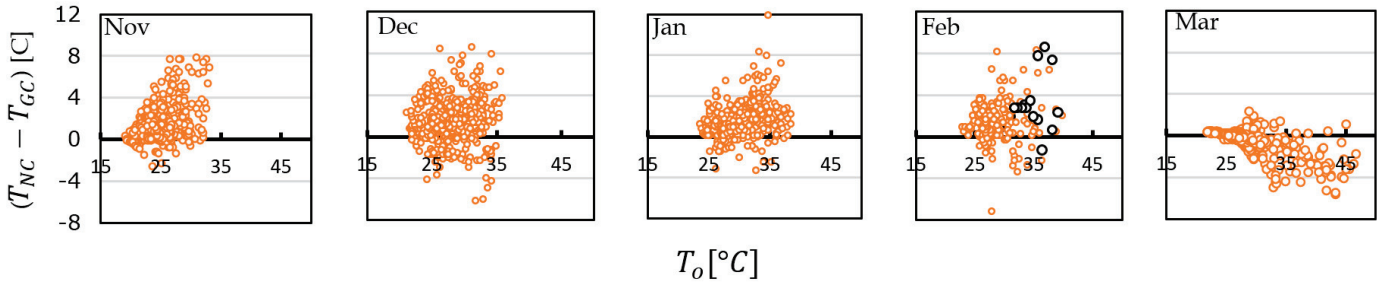



**Figure 6.** The difference between the temperature of NC and GC recorded during the peak solar radiation hours. The horizontal axis shows the outside temperature, and the vertical axis shows the difference of temperature between NC and GC. The black dots in late summer (February) corresponds to 1 February 2022 data points shown in Figure 5.

The absence of a plant delayed the cooling period in both the NC and WB blinds. As in the summer months (December, January, and February), the mean temperature in the after-peak hours (16:30–20:30 hrs) in GC was 1.5 ± 0.05 °C lesser than NC and 1 ± 0.05 °C than WB. This difference even reached up to 8 °C and 4 °C, respectively, on hotter days in particular hours. In early autumn (March), the change in the solar angle due to the seasonal variations resulted in high peaks noticed in the outside temperature.

The difference of air temperature between the base case module (NC) and GC, shown in Figure 6 during the peak solar radiation hours, clearly show the significance of a living plant medium. From late spring (November) to late summer (February), more than 90% of values were positive. In those positive values, more than 95% were between 0–4 °C. The maximum difference reached up to 11 °C in January. A temperature difference of 1–3 °C with an indoor plant medium was noticed in the indoor studies [70]. The seasonal shift in early autumn (Mar) shows more than 90% negative values. Though a short hot spell increased the outside temperature above 40 °C again and even up to 47 °C but the difference was in the negative, it was because, due to the change in the solar angle, the solar radiation was hitting the sensor probes in the GC module directly.

### *4.3. Temperature and Relative Humidity (during Solar and Non-Solar Radiation Hours)*

From the box plot data shown in Figure 7, it is important to note that the mean value (x) and the median line are at the lowest in the GC module from late spring (November) to late summer (February). This shows the overall performance of the GC prototype to regulate the indoor temperature inside the module and keep it around or within the ASHRAE range. The evapotranspiration effect [67] of the GC causes this cooling effect inside the module. Moreover, on an average hourly basis, GC is 1.3 °C and 0.6 °C cooler than NC and WB, respectively. This can be verified by a meta-analysis study of green spaces [71]. WB had the lowest average maximum daily temperature, followed by GC and NC; this can be explained by the reflection of the solar radiation. However, some radiation still comes inside the WB and the heat then gets entrapped as with NC. Therefore, this entrapped heat in the form of high thermal mass [72] does not allow the WB and NC to get low quickly, compared to GC which had plants.

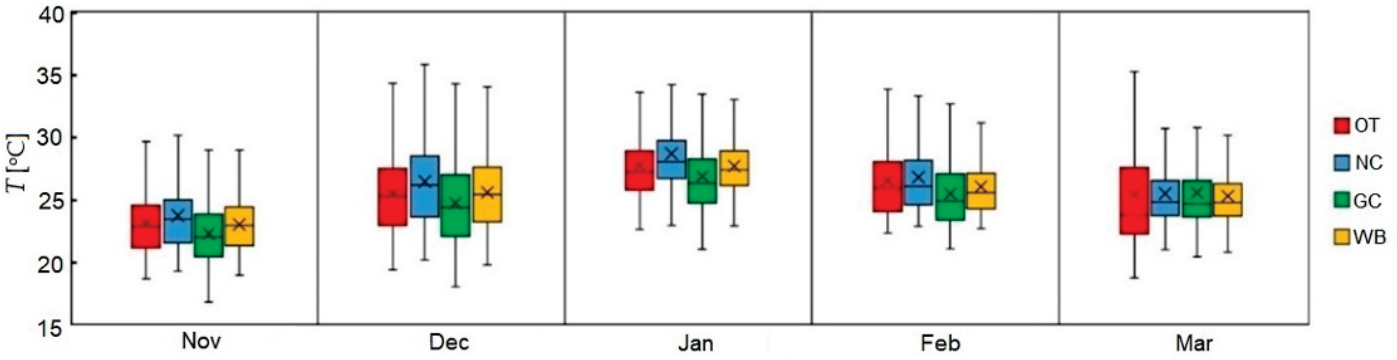



**Figure 7.** The complete recorded temperature data (solar and non-solar radiation hours) shown as box plots with error bars for outside temperature (OT) and the three modules (NC, GC, and WB) every month. The box plot shows a median (solid middle line), mean value (marker—(×)), the interquartile ranges (upper and lower limit lines of the boxes), and the range of maximum to minimum values (the whiskers), except for "outliers".

The maximum and minimum temperatures also ranged significantly within each season (Figure 7). It was important to note that the temperature range increased during the seasonal shifts; e.g., the largest temperature range overall was recorded in the NC module during late spring (November) (min = 23 °C, max = 45 °C), while the maximum in the GC was found in early autumn (March) between 20 °C (min) and 40 °C (max). The maximum variation in the outside temperature was found in March (min = 18 °C, max = 47 °C). The high temperatures of NC are due to entrapped heat between the window glass and the plexiglass sheet accumulated during the solar radiation hours of the day. The lack of ventilation and the trapping of the long wavelength radiation inside the NC caused a greenhouse effect [73].

The RH data are shown in Figure 8. GC had the highest RH in all the modules from late spring (November) till late summer (February). On a daily average basis, in late spring (November), the RH of GC was greater than OT, NC, and WB by 9%, 6%, and 7%, respectively. In the summer months (December, January, and February), this difference was 3.62%, 7.2%, and 5.72%. The high RH values of GC were due to transpiration, as the water travels from the root to the plant leaves, where it turns into water vapor and is released into the atmosphere [68]. Therefore, green plants can increase indoor relative humidity [74] and also regulate air temperature [75]. The minimum values were all recorded in the afternoon because the cooler morning air is closer to saturation than the hot afternoon air, even with the same amount of water vapor. The season shift from late summer to early autumn lowers the RH in GC and the difference is 1% approximately each between GC,NC and GC,WB. In March, the rise in RH values is due to the dip in the external and internal temperatures [76], as the weather becomes cooler, causing the air to be moist.

The maximum RH observed in GC was 93% on 23 December 2021, whereas the maximum outside RH was 94%, recorded in March. The average hourly peak was observed at 06:30 hrs. A regular pattern of a dip in relative humidity was seen in all modules from 09:00–15:30 hrs, because an increase in solar radiation decreases the vapor content in the air [77].

Practically, 98% of occupants are thermally satisfied when the temperature and relative humidity integration take place in the comfort zone suggested by ASHRAE Standard 55 [78]. Consequently, a person will feel almost exactly as cool at 24 °C and 60% relative humidity as at 26 °C and 30% relative humidity [36]. Moreover, the local standards of New South Wales (an Australian state) recommend a temperature of 20–26 °C [79]. Based on these standards, the frequencies of temperature and relative humidity are shown in Figure 9. It shows that the GC module had the maximum frequencies of temperatures falling between the recommended range for the occupants. The GC temperature complied with 66% of the acceptance limits of ASHRAE and NSW (20–26 °C), greater than WB (57%) and NC (51%).

In Figure 9, the frequencies of the relative humidities show that GC had the maximum frequencies falling between 70 to 80% compared to the other two modules.

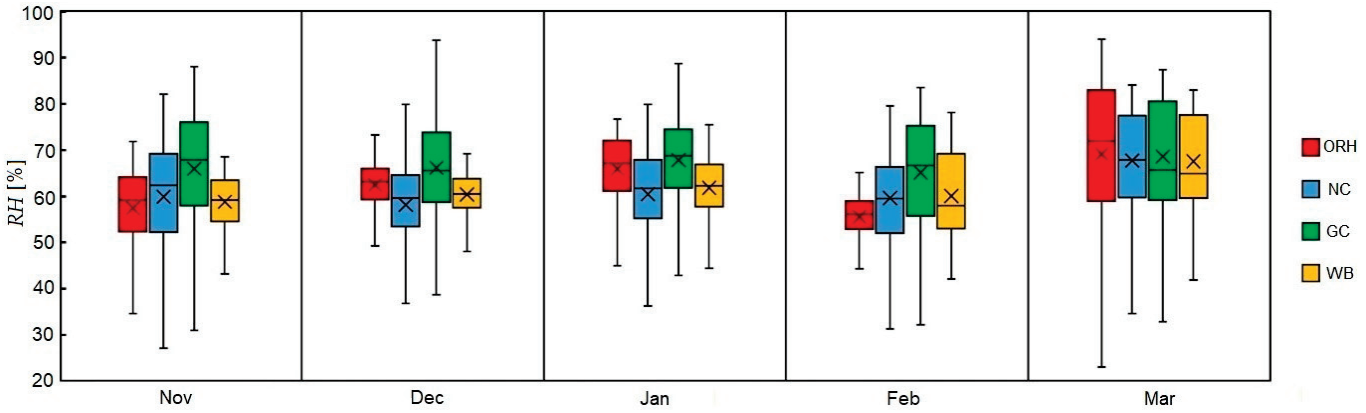



**Figure 8.** The complete recorded relative humidity data (solar and non-solar radiation hours) shown as box plots with error bars for outside temperature (OT) and inside the three modules (NC, GC, and WB) in every month. The box plot shows a median (solid middle line), mean value (marker—(×)), the interquartile ranges (upper and lower limit lines of the boxes), and the range of maximum to minimum values (the whiskers), except for "outliers".

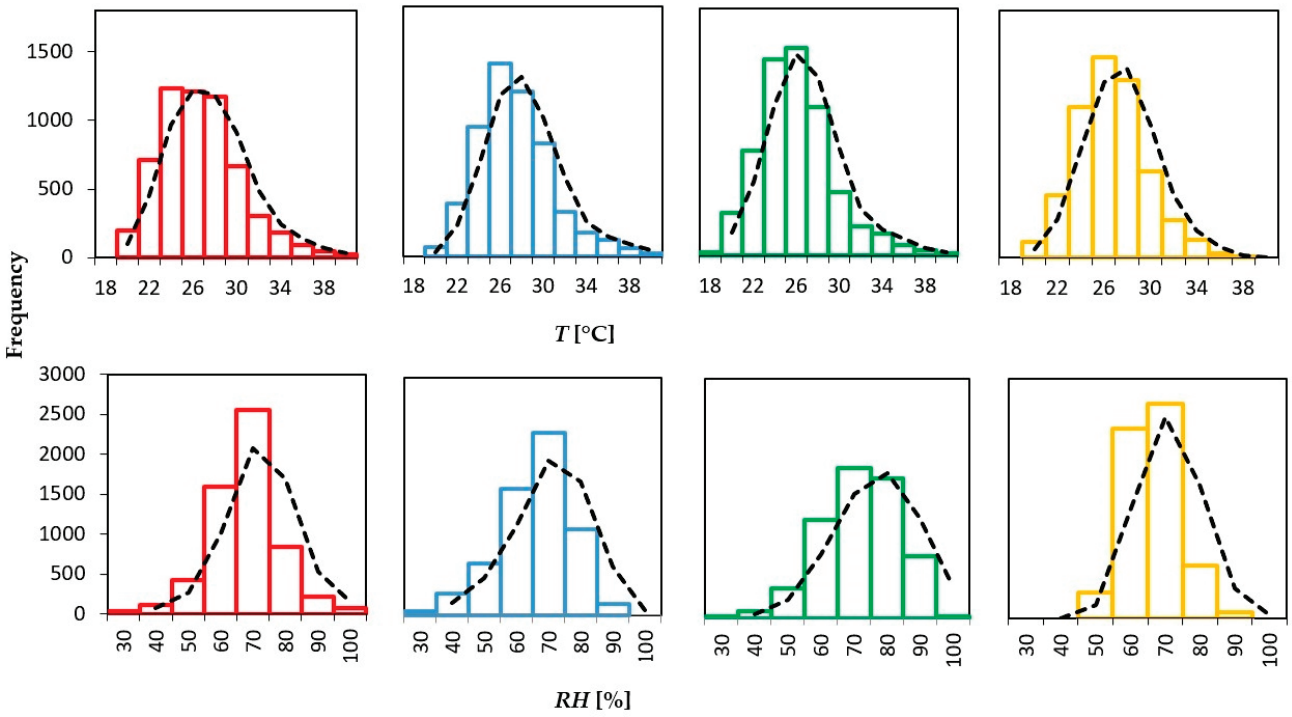



**Figure 9.** The frequencies of the temperature and relative huimidities inside the modules with moving average lines (black dotted) shown in black. The horizontal axis lines show a certain range of temperature and RH. The vertical axis line shows the frequency of occurrence of temperature and RH.

### *4.4. Air Quality*

The air quality comparison between the GC and WB did not show a significant difference compared to each other, as shown in Figure 10. To examine the data of the Air Quality (AQ), the arithmetic theory of the null hypothesis was used [80], suggesting that no significant difference exists in the set of observed variables (GC-AQ and WB-AQ) between the two sets of observed data. The null hypothesis statement is that the difference in the mean of the AQ of the GC module is equal or not different from the mean of the

WB-AQ. The test was carried out for two time frames, 02:00–16:00 hrs and 16:00–02:00 hrs. It was found that, from 02:00–16:00 hrs, the *p*-value was 0.08 (>0.05), which means the null hypothesis was accepted, but, from 16:00–02:00 hrs, the *p* was 0.0001 (<0.05) and the null hypothesis was rejected. This means that, in the evening, the difference was significant and the GC module was more effective at decreasing the pollution compared to the WB module.

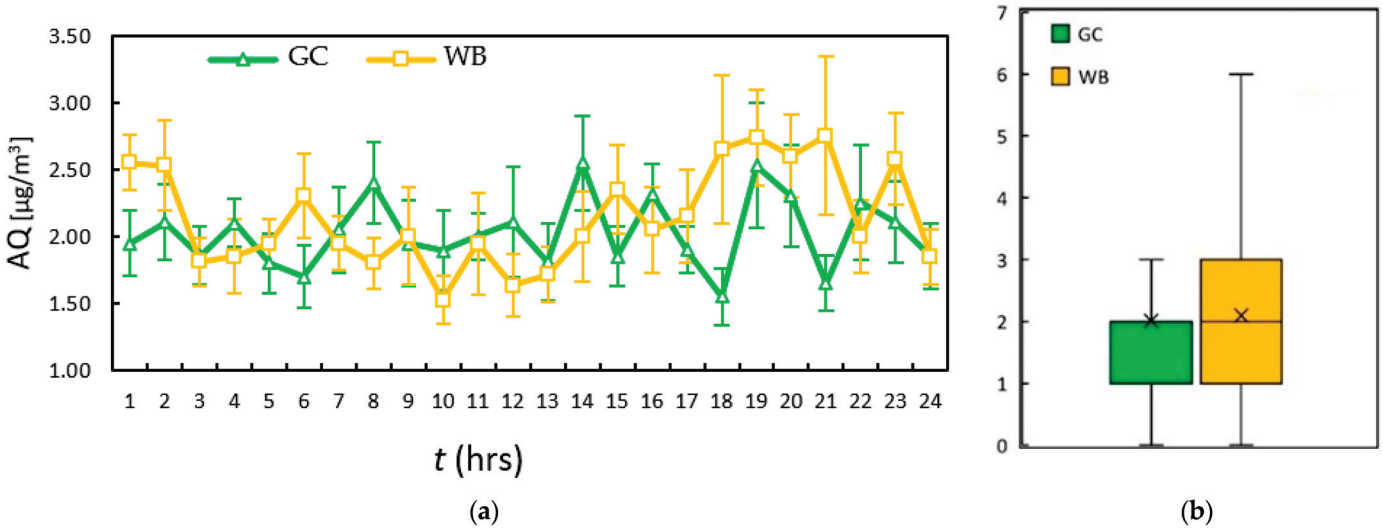



**Figure 10.** (**a**) Hourly mean data of AQ for GC and WB modules. The error bars were calcualted using standard error (SE); formula: SE = Standard Deviation/$\sqrt{}$ (sample size). These mean data were calculated from the complete raw data measured every 30 min from 1 March 2022 to 21 March 2022. (**b**) The box plot data distribution of the AQ data. The box plot shows median (solid middle line), mean marker (×) and the interquartile ranges; the whiskers give the range of maximum to minimum, except for "outliers".

Because of the lack of ventilation in both the modules, the air quality remained fairly constant in the range of healthy standards for air [81], except in the period between 1800 to 2200 hrs, when the AQ values increased in the module without GC, indicating higher pollution in the evening hours. The daily maximum, minimum and mean values of all the variables is shown in Table 2.

**Table 2.** Summary of the temperature, relative humidity, and air quality measured during the experimental period (solar + non-solar radiation hours). The standard errors are shown for the daily mean, maximum daily mean, and minimum daily mean. The daily mean was the average of all the values recorded for a variable. The maximum daily mean was found by finding the maximum value of a variable in 24 h and then finding the average of all those maximum values; the same applies for the minimum daily mean. The maximum and minimum values correspond to the highest and lowest values recorded for a variable during the whole data collection period.

| | OT (°C) | NC (°C) | GC (°C) | WB (°C) | ORH (%) | NC (%) | GC (%) | WB (%) | GCAQ (µg/m³) | WBAQ (µg/m³) |
|---|---|---|---|---|---|---|---|---|---|---|
| Daily Mean | 25.72 ± 0.22 | 26.39 ± 0.22 | 25.05 ± 0.20 | 25.64 ± 0.21 | 60.07 ± 1.30 | 60.74 ± 0.78 | 66.75 ± 0.77 | 61.43 ± 0.62 | 1.99 ± 0.09 | 2.19 ± 0.09 |
| Max daily mean | 31.30 ± 0.41 | 31.99 ± 0.42 | 30.39 ± 0.37 | 28.89 ± 0.29 | 65.37 ± 1.41 | 68.34 ± 0.67 | 77.09 ± 0.81 | 64.66 ± 0.62 | 0.87 ± 0.18 | 1.04 ± 0.22 |
| Min daily mean | 22.82 ± 0.21 | 23.90 ± 0.20 | 21.94 ± 0.18 | 23.55 ± 0.19 | 51.00 ± 1.35 | 46.94 ± 1.23 | 54.17 ± 1.02 | 57.08 ± 0.74 | 0.14 ± 0.03 | 0.13 ± 0.03 |
| Max | 46.90 | 44.85 | 39.99 | 36.72 | 0.00 | 94.00 | 84.12 | 93.78 | 9 | 11 |
| Min | 18.73 | 19.33 | 16.85 | 19.01 | 0.00 | 22.00 | 19.98 | 29.67 | 0 | 0 |

Overall, the plant (Philodendron cordatum) remained in good health, though some issues with the growth of the plant were anticipated, as Philodendron cordatum does not tolerate direct sunlight. However, it was found that the plant adapted relatively well to the solar radiation. Due to the lack of ventilation, in the last few weeks (in March) of the experiment, the number of brown (dead) leaves started to increase but, by then, the data collection process was completed. As the prototype potential difference was at

the maximum in the summer months, this indicated that it is a plant that requires less maintenance, that can adapt to harsh environmental conditions.

## 5. Conclusions

Vertical greening in form of green walls or living facades are used in buildings to improve air quality, reduce the urban heat island effect, provide habitat for wildlife, reduce noise pollution, and enhance the biophilic character of buildings. On the other hand, the indoor vertical greening system is less common and poorly investigated. This research is unique in developing an innovative indoor vertical greening in the form of a green curtain within an indoor setting of a prototype room. The green curtain provides to the occupants full control of the amount of sunlight that is allowed into the indoor environment based on the innovative rotating mechanism of its modules, allowing us to adjust the indoor natural light and the exposure of the plants to the required solar radiation needed for effective evapotranspiration. We demonstrated positive impacts on air temperature and air quality consistent with findings from outdoor greening studies. It was found that, during the peak solar radiation hours from late spring (November) to late summer (February), the difference between NC and GC air temperatures was mostly between 0–4 °C. On hotter days, during the peak hours, with regard to the maximum difference between NC, GC, and WB, GC was as high as 8 °C and 4 °C, respectively. In the after-peak hours, during the summer months, the GC module was cooler than the NC and WB modules by 1 °C and 1.5 °C, respectively. Overall, the GC created a climate in an intermediate space of the module that was characterized by lower temperature, heat absorption, higher humidity, and improved air quality in the evening hours. While the GC would not significantly affect the temperature/humidity indoors, it produces a significant reduction of the heat flow in the building envelope due to the combined effect of evapotranspiration, reflected solar radiation, and photosynthesis.

The implication of the initial findings is vast, as a simple indoor solution without any retrofitting requirement or an alternative to an energy-saving retrofit strategy for windows provides a feasible option to mitigate heat gain. Moreover, we optimized two main thermal comfort factors, air temperature and relative humidity, in the desired range, that improve thermal comfort. In addition, the design adopted a biophilic design approach that creates a natural indoor environment, providing the benefits of biophilia by bringing the green outdoors indoors. High humidity levels were observed near the living wall due to plant evapotranspiration, which is beneficial in the case of dry indoor environments.

### *5.1. Direction for Future Studies and Methodological Recommendations*

The future developments of the research will aim to investigate the performance and benefits of the GC when applied to realistic settings in the form of larger module areas. As for a more real-world setting, proper ventilation is advised to avoid problems associated with excessive moisture because there was reduced air circulation from outside to inside or vice versa. The model can also be studied for naturally ventilated buildings, where more air circulation effects on the plant growth and comfort parameters can be studied. The prototype should also be tested in other seasons, e.g., in winter or early spring. To investigate the fluctuations of the indoor operative temperature over the entire year under various indoor air temperature set-points, a computer simulation model can be developed using a BIM (building information modeling) tool, e.g., Integrated Environmental Solutions [82] or Energy Plus [83]. Computer simulations should account for the thermal mass effect as observed in the experiments reported here. Moreover, a numerical model assessment of the GC prototype is recommended for future studies to evaluate the behavior of the prototype when upscaled. It is important to arrange all the necessary equipment for measuring all the variables, e.g., evapotranspiration rate, photosynthetic rate, latent heat of vaporization, short/long incident/reflected solar radiation, and temperature sensors, inside the leaves of the GC. Moreover, multiple sensors for each variable should be used to improve indoor environmental quality management [84].

However, the design of the prototype for every plant may be different, depending on the plant species' growth rate and shape; e.g., some plant species grow from top to bottom, others sideways. To further improve the prototype design, we should minimize human interaction by integrating it with BEMS (Building Energy Management Systems). Moreover, some other benefits of plants should be studied, e.g., carbon reduction from a building performance point of view, and numerous health and well-being, psychological, cognitive, and behavioral benefits from the human performance point of view. All the recommendations can assist in promoting an affordable and biophilic solution to improve indoor environmental quality (IEQ).

### *5.2. Limitations*

This study was not benchmarked with other studies because no rotating-mechanism-based indoor plant was found in the literature. However, in the future, this study can be considered as a benchmark of calibration for other plants. Some consideration can also be given to adverse plant-related effects because those effects have received very little or no attention from built-environment-focused studies.

Human habitation in cities occurs in indoor environments and this study has provided an opportunity to enhance building occupant health, well-being, and comfort. This research further identifies the need for future research to consider and integrate plant science aspects, providing a foundation for the inclusion of indoor living walls in urban built environments.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings13051307/s1. Figure S1: Daily pattern of solar radiation intensity during the solar radiation hours from 8 December 2021–22 March 2022. The redline shows the outside solar radiation intensity measured by the sensor installed outside and the green line shows the radiation that passes through the window glass. The flat line from 22–27 December (2021), shows the data was not recorded. Figure S2: Daily pattern of temperatures recorded outside, and in the three modules (NC, GC, WB). The pattern shows three-time frames; before the peak hours, at the peak hours, and after the peak hours. The time frames have changed on daily basis based on the solar angle. Figure S3: Complete Relative humidity profile pattern recorded every 30 mins for outside environment and in the three modules (NC, GC, and WB). This measurement is from 4 November 2021 to 21 March 2022.

**Author Contributions:** The author contribution is as follows: conceptualization, N.W. and F.A.-M.; methodology, G.Q. and A.B.; validation, G.Q., F.A.-M. and A.B.; formal analysis, G.Q.; investigation, G.Q.; data curation, G.Q.; writing—original draft preparation, G.Q.; writing—review and editing, G.Q., F.A.-M. and A.B.; visualization, G.Q., F.A.-M. and A.B.; supervision, F.A.-M. and A.B.; project administration, F.A.-M. and G.Q. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Data is available on request.

**Acknowledgments:** The authors express appreciation to Rahmee Chowdhury, Gaurav Poddar, and Janane Yogesan for assisting in the CAD model of the prototype. The authors also thank Theo Gresley-Daines (The University of Sydney) for building the GC prototype.

**Conflicts of Interest:** All authors have seen and approved the final version of the manuscript being submitted. They warrant that the article is the author's original work, has not received prior publication, and is not under consideration for publication elsewhere.

## Appendix A Green Curtain Prototype Experiment Components

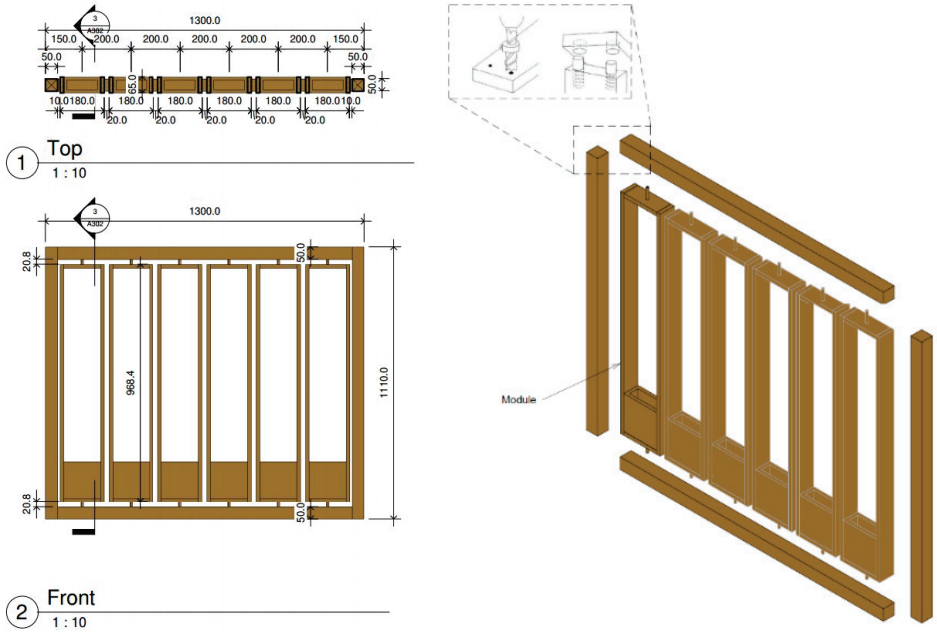



**Figure A1.** Front view and isometric 3D modeled view of all the components of the green curtain prototype. All units in mm.

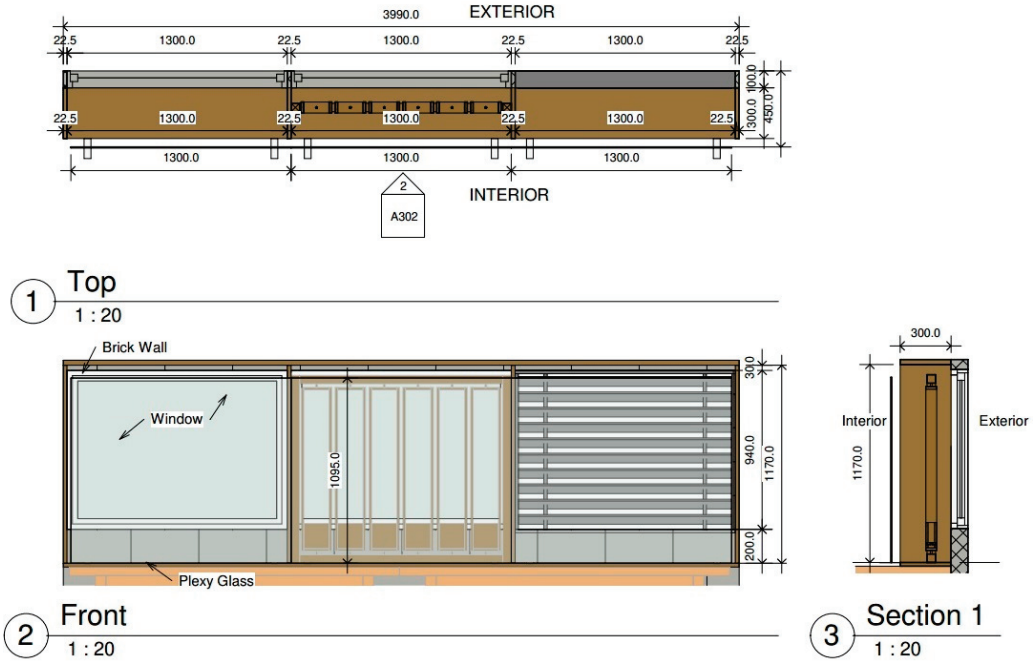



**Figure A2.** Section and top view of all the components of the experimental set-up. All units in mm.

## References

1. Kaloustian, N.; Diab, Y. Effects of urbanization on the urban heat island in Beirut. *Urban Clim.* **2015**, *14*, 154–165. [CrossRef]
2. Wang, S.; Gao, S.; Li, S.; Feng, K. Strategizing the relation between urbanization and air pollution: Empirical evidence from global countries. *J. Clean. Prod.* **2020**, *243*, 118615. [CrossRef]
3. Tam, B.Y.; Gough, W.A.; Mohsin, T. The impact of urbanization and the urban heat island effect on day to day temperature variation. *Urban Clim.* **2015**, *12*, 1–10. [CrossRef]
4. Arfanuzzaman, M.; Rahman, A.A. Sustainable water demand management in the face of rapid urbanization and ground water depletion for social–ecological resilience building. *Glob. Ecol. Conserv.* **2017**, *10*, 9–22. [CrossRef]

5. Miller, J.D.; Hutchins, M. The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. *J. Hydrol. Reg. Stud.* **2017**, *12*, 345–362. [CrossRef]
6. Cao, X.; Dai, X.; Liu, J. Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade. *Energy Build.* **2016**, *128*, 198–213. [CrossRef]
7. Huang, M.; Hao, X.; Li, C. Heat and Mass Transfer of Evaporative Wall and Its Cooling Load Calculation. *Procedia Eng.* **2017**, *205*, 2762–2770. [CrossRef]
8. Cetin, K.S.; Fathollahzadeh, M.H.; Kunwar, N.; Do, H.; Tabares-Velasco, P.C. Development and validation of an HVAC on/off controller in EnergyPlus for energy simulation of residential and small commercial buildings. *Energy Build.* **2019**, *183*, 467–483. [CrossRef]
9. Spiru, P.; Simona, P.L. A review on interactions between energy performance of the buildings, outdoor air pollution and the indoor air quality. *Energy Procedia* **2017**, *128*, 179–186. [CrossRef]
10. (EAP) USEPA. *Introduction to Indoor Air Quality United States*; EPA: Washington, DC, USA, 2020. Available online: https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality#:~:text=Inadequate%20ventilation%20can%20increase%20indoor,increase%20concentrations%20of%20some%20pollutants (accessed on 6 March 2022).
11. ASHRAE. *Indoor Air Quality (IAQ)*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2020. Available online: https://xp20.ashrae.org/terminology/index.php?term=indoor%20air%20quality%20(IAQ) (accessed on 5 April 2022).
12. (Institute) IIWB. The Value of WELL 2014. Available online: https://www.wellcertified.com/certification/v1/ (accessed on 10 January 2021).
13. (Council) UUSgb. Green Building 101: What Is Indoor Environmental Quality? *2014*. Available online: https://www.usgbc.org/articles/green-building-101-what-indoor-environmental-quality (accessed on 15 December 2021).
14. Al horr, Y.; Arif, M.; Katafygiotou, M.; Mazroei, A.; Kaushik, A.; Elsarrag, E. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *Int. J. Sustain. Built Environ.* **2016**, *5*, 1–11. [CrossRef]
15. Zhong, W.; Schröder, T.; Bekkering, J. Biophilic design in architecture and its contributions to health, well-being, and sustainability: A critical review. *Front. Archit. Res.* **2022**, *11*, 114–141. [CrossRef]
16. Reed, R.G.; Wilkinson, S.J. The increasing importance of sustainability for building ownership. *J. Corp. Real Estate* **2005**, *7*, 339–350. [CrossRef]
17. Al Horr, Y.; Arif, M.; Kaushik, A.; Mazroei, A.; Elsarrag, E.; Mishra, S. Occupant productivity and indoor environment quality: A case of GSAS. *Int. J. Sustain. Built Environ.* **2017**, *6*, 476–490. [CrossRef]
18. ASHRAE. *Indoor Environmental Quality (IEQ)*; ASHRAE: Atlanta, GA, USA, 2020. Available online: https://xp20.ashrae.org/terminology/index.php?term=indoor%20environment%20quality%20(IEQ)#:~:text=)%22%20Back%20%7C%20Next-,indoor%20environment%20quality%20(IEQ),%2C%20healthy%2C%20and%20comfortable%20buildings (accessed on 27 November 2022).
19. Bratman, G.N.; Daily, G.C.; Levy, B.J.; Gross, J.J. The benefits of nature experience: Improved affect and cognition. *Landsc. Urban Plan.* **2015**, *138*, 41–50. [CrossRef]
20. Europe WROf. *Urban Green Spaces and Health—A Review of Evidence*; WHO (World Health Organization): Copenhagen, Denmark, 2016.
21. Tyrväinen, L.; Ojala, A.; Korpela, K.; Lanki, T.; Tsunetsugu, Y.; Kagawa, T. The influence of urban green environments on stress relief measures: A field experiment. *J. Environ. Psychol.* **2014**, *38*, 1–9. [CrossRef]
22. Li, F.; Zheng, W.; Wang, Y.; Liang, J.; Xie, S.; Guo, S.; Li, X.; Yu, C. Urban Green Space Fragmentation and Urbanization: A Spatiotemporal Perspective. *Forests* **2019**, *10*, 333. [CrossRef]
23. Darlington, A. *Ecology of Walls*; Heinemann Educational Books: London, UK, 1981.
24. Wilkinson, S.; Brown, P.; Ghosh, S. Expanding the living architecture in Australia. Green Cities. 2018. Available online: https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/gc15001/ (accessed on 6 March 2022).
25. Pérez, G.; Rincón, L.; Vila, A.; González, J.M.; Cabeza, L.F. Green vertical systems for buildings as passive systems for energy savings. *Appl. Energy* **2011**, *88*, 4854–4859. [CrossRef]
26. Jim, C.Y. Greenwall classification and critical design-management assessments. *Ecol. Eng.* **2015**, *77*, 348–362. [CrossRef]
27. Ip, K.; Lam, M.; Miller, A. Shading performance of a vertical deciduous climbing plant canopy. *Build. Environ.* **2010**, *45*, 81–88. [CrossRef]
28. Wong, I.; Baldwin, A.N. Investigating the potential of applying vertical green walls to high-rise residential buildings for energy-saving in sub-tropical region. *Build. Environ.* **2016**, *97*, 34–39. [CrossRef]
29. Feitosa, R.C.; Wilkinson, S. Retrofitted green roofs and walls and improvements in thermal comfort. *AIP Conf. Proc.* **2017**, *1856*, 020006.
30. Castiglia Feitosa, R.; Wilkinson, S.J.; Oliveira, B.; Hacon, S. Wind and greenery effects in attenuating heat stress: A case study. *J. Clean. Prod.* **2021**, *291*, 125919. [CrossRef]
31. Stec, W.J.; van Paassen, A.H.C.; Maziarz, A. Modelling the double skin façade with plants. *Energy Build.* **2005**, *37*, 419–427. [CrossRef]
32. Cheng, C.Y.; Cheung, K.K.S.; Chu, L.M. Thermal performance of a vegetated cladding system on facade walls. *Build. Environ.* **2010**, *45*, 1779–1787. [CrossRef]

33. Cuce, E. Thermal regulation impact of green walls: An experimental and numerical investigation. *Appl. Energy* **2017**, *194*, 247–254. [CrossRef]
34. Akbari, H.; Kurn, D.M.; Bretz, S.E.; Hanford, J.W. Peak power and cooling energy savings of shade trees. *Energy Build.* **1997**, *25*, 139–148. [CrossRef]
35. Haggag, M.; Hassan, A.; Qadir, G. Energy and Economic Performance of Plant-Shaded Building Façade in Hot Arid Climate. *Sustainability* **2017**, *9*, 2026. [CrossRef]
36. Bianco, L.; Serra, V.; Larcher, F.; Perino, M. Thermal behaviour assessment of a novel vertical greenery module system: First results of a long-term monitoring campaign in an outdoor test cell. *Energy Effic.* **2017**, *10*, 625–638. [CrossRef]
37. Scarpa, M.; Mazzali, U.; Peron, F. Modeling the energy performance of living walls: Validation against field measurements in temperate climate. *Energy Build.* **2014**, *79*, 155–163. [CrossRef]
38. Seyam, S. The impact of greenery systems on building energy: Systematic review. *J. Build. Eng.* **2019**, *26*, 100887. [CrossRef]
39. Mayrand, F.; Clergeau, P.; Vergnes, A.; Madre, F. Chapter 3.13–Vertical Greening Systems as Habitat for Biodiversity. In *Nature Based Strategies for Urban and Building Sustainability*; Pérez, G., Perini, K., Eds.; Butterworth-Heinemann: Oxford, UK, 2018; pp. 227–237.
40. Perini, K.; Rosasco, P. Is greening the building envelope economically sustainable? An analysis to evaluate the advantages of economy of scope of vertical greening systems and green roofs. *Urban For. Urban Green.* **2016**, *20*, 328–337. [CrossRef]
41. Hoyano, A. Climatological uses of plants for solar control and the effects on the thermal environment of a building. *Energy Build.* **1988**, *11*, 181–199. [CrossRef]
42. Mathew, A.; Khandelwal, S.; Kaul, N. Investigating spatial and seasonal variations of urban heat island effect over Jaipur city and its relationship with vegetation, urbanization and elevation parameters. *Sustain. Cities Soc.* **2017**, *35*, 157–177. [CrossRef]
43. Jim, C.Y. Thermal performance of climber greenwalls: Effects of solar irradiance and orientation. *Appl. Energy* **2015**, *154*, 631–643. [CrossRef]
44. He, Y.; Yu, H.; Ozaki, A.; Dong, N.; Zheng, S. An investigation on the thermal and energy performance of living wall system in Shanghai area. *Energy Build.* **2017**, *140*, 324–335. [CrossRef]
45. Fernández-Cañero, R.; Urrestarazu, L.P.; Franco Salas, A. Assessment of the Cooling Potential of an Indoor Living Wall using Different Substrates in a Warm Climate. *Indoor Built Environ.* **2011**, *21*, 642–650. [CrossRef]
46. Baughman, A.; Arens, E. Indoor humidity and human health–Part I: Literature review of health effects of humidity-influenced indoor pollutants. *ASHRAE Trans.* **1996**, *102*, 193–211.
47. Papadakis, G.; Tsamis, P.; Kyritsis, S. An experimental investigation of the effect of shading with plants for solar control of buildings. *Energy Build.* **2001**, *33*, 831–836. [CrossRef]
48. Wang, Y.; Bakker, F.; de Groot, R.; Wörtche, H. Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review. *Build. Environ.* **2014**, *77*, 88–100. [CrossRef]
49. Moya, T.A.; van den Dobbelsteen, A.; Ottele, M.; Bluyssen, P.M. A review of green systems within the indoor environment. *Indoor Built Environ.* **2019**, *28*, 298–309. [CrossRef]
50. Cetin, M.; Sevik, H. Measuring the Impact of Selected Plants on Indoor $CO_2$ Concentrations. *Pol. J. Environ. Stud.* **2016**, *25*. [CrossRef] [PubMed]
51. Jones, A.P. Indoor air quality and health. *Atmos. Environ.* **1999**, *33*, 4535–4564. [CrossRef]
52. Ramage, M.; Burridge, H.; Wicher, M.; Fereday, G.; Reynolds, T.; Shah, D.; Wu, G.; Yu, L.; Fleming, P.; Densley-Tingley, D.; et al. The wood from the trees: The use of timber in construction. *Renew. Sustain. Energy Rev.* **2017**, *68*, 333–359. [CrossRef]
53. Kwon, M.; Remøy, H.; van den Dobbelsteen, A.; Knaack, U. Personal control and environmental user satisfaction in office buildings: Results of case studies in the Netherlands. *Build. Environ.* **2019**, *149*, 428–435. [CrossRef]
54. Today, P.C. Growing Heartleaf Philodendron: Philodendron Cordatum Care 2019. Available online: https://plantcaretoday.com/philodendron-cordatum.html (accessed on 10 December 2021).
55. Katul, G.G.; Oren, R.; Manzoni, S.; Higgins, C.; Parlange, M.B. Evapotranspiration: A process driving mass transport and energy exchange in the soil-plant-atmosphere-climate system. *Rev. Geophys.* **2012**, *50*. [CrossRef]
56. Zipfel, C.; Robatzek, S. Pathogen-associated molecular pattern-triggered immunity: Veni, vidi ... ? *Plant Physiol.* **2010**, *154*, 551–554. [CrossRef]
57. Monteith, J. Solar radiation and productivity in tropical ecosystems. *J. Appl. Ecol.* **1972**, *9*, 747–766. [CrossRef]
58. Hussain, C.M. *Handbook of Environmental Materials Management*; Springer: Cham, Switzerland, 2019.
59. Kiehl, J.T.; Trenberth, K.E. Earth's Annual Global Mean Energy Budget. *Bull. Am. Meteorol. Soc.* **1997**, *78*, 197–208. [CrossRef]
60. Gates, D.M. Leaf Temperature and Transpiration1. *Agron. J.* **1964**, *56*, 273–277. [CrossRef]
61. Zhang, L.; Deng, Z.; Liang, L.; Zhang, Y.; Meng, Q.; Wang, J.; Santamouris, M. Thermal behavior of a vertical green facade and its impact on the indoor and outdoor thermal environment. *Energy Build.* **2019**, *204*, 109502. [CrossRef]
62. Hargreaves, G.H.; Samani, Z.A. Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.* **1985**, *1*, 96–99. [CrossRef]
63. Hipps, L.E.; Asrar, G.; Kanemasu, E.T. Assessing the interception of photosynthetically active radiation in winter wheat. *Agric. Meteorol.* **1983**, *28*, 253–259. [CrossRef]
64. Lide, D.R. *The CRC Handbook of Chemistry and Physics*, 85th ed.; CRC Press: Boca Raton, FL, USA, 2004.
65. Australia BoM. New South Wales in 2021: Very Wet Overall and Relatively Cool 2021. Available online: http://www.bom.gov.au/climate/current/annual/nsw/summary.shtml (accessed on 5 May 2022).

66. Page, J. Chapter IIA-1–The Role of Solar-Radiation Climatology in the Design of Photovoltaic Systems. In *Practical Handbook of Photovoltaics*, 2nd ed.; McEvoy, A., Markvart, T., Castañer, L., Eds.; Academic Press: Boston, MA, USA, 2012; pp. 573–643.
67. Groh, J.; Pütz, T.; Gerke, H.H.; Vanderborght, J.; Vereecken, H. Quantification and Prediction of Nighttime Evapotranspiration for Two Distinct Grassland Ecosystems. *Water Resour. Res.* **2019**, *55*, 2961–2975. [CrossRef]
68. Deng, L.; Deng, Q. The basic roles of indoor plants in human health and comfort. *Environ. Sci. Pollut. Res.* **2018**, *25*, 36087–36101. [CrossRef]
69. Jain, P.C. Greenhouse effect and climate change: Scientific basis and overview. *Renew. Energy* **1993**, *3*, 403–420. [CrossRef]
70. Abdo, P.; Huynh, B.P. An experimental investigation of green wall bio-filter towards air temperature and humidity variation. *J. Build. Eng.* **2021**, *39*, 102244. [CrossRef]
71. Bowler, D.E.; Buyung-Ali, L.; Knight, T.M.; Pullin, A.S. Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landsc. Urban Plan.* **2010**, *97*, 147–155. [CrossRef]
72. Dunster, B.; Simmons, C.; Gilbert, B. *Thermal Mass*; Taylor & Francis: London, UK, 2021; pp. 185–186.
73. Kweku, D.W.; Bismark, O.; Maxwell, A.; Desmond, K.A.; Danso, K.B.; Oti-Mensah, E.A.; Quachie, A.T.; Adormaa, B.B. Greenhouse effect: Greenhouse gases and their impact on global warming. *J. Sci. Res. Rep.* **2018**, *17*, 1–9. [CrossRef]
74. Salt, D.E.; Blaylock, M.; Kumar, N.P.; Dushenkov, V.; Ensley, B.D.; Chet, I.; Raskin, I. Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. *Bio/Technology* **1995**, *13*, 468–474. [CrossRef]
75. Liu, F.; Yan, L.; Meng, X.; Zhang, C. A review on indoor green plants employed to improve indoor environment. *J. Build. Eng.* **2022**, *53*, 104542. [CrossRef]
76. Hyndman, B. Chapter 91–Heating, ventilation, and air conditioning. In *Clinical Engineering Handbook*, 2nd ed.; Iadanza, E., Ed.; Academic Press: Cambridge, MA, USA, 2020; pp. 662–666.
77. Lightfoot, H. Earth's Temperature Versus the Sun, Water Vapor and $CO_2$. *J. Basic Appl. Sci.* **2021**, *17*, 44–53. [CrossRef]
78. American National Standards Institute. *Thermal Environmental Conditions for Human Occupancy*; American Society of Heating, Refrigerating and Air-Conditioning Engineers: Atlanta, GA, USA, 2004.
79. NSW. Maintaining Thermal Comfort in Indoor Work Environments: Safework NSW. 2022. Available online: https://www.safework.nsw.gov.au/resource-library/heat-and-environment/maintaining-thermal-comfort-in-indoor-work-environments (accessed on 22 February 2022).
80. Anderson, D.R.; Burnham, K.P.; Thompson, W.L. Null hypothesis testing: Problems, prevalence, and an alternative. *J. Wildl. Manag.* **2000**, *64*, 912–923. [CrossRef]
81. (EPA) Epa. *Revised Air Quality Standards for Particle Pollution and Updates to the Air Quality Index (aqi). The National Ambient Air Quality Standards for Particle Pollution*; EPA: Washington, DC, USA, 2012.
82. Solutions, I.E. Help Manual 2019. Available online: https://help.iesve.com/ve2019/ (accessed on 21 September 2022).
83. EnergyPlus Manual 2021. Available online: https://energyplus.net/documentation (accessed on 21 September 2022).
84. Al-Samman, S.; Eftekhari, M.; Coakley, D.; Angelopoulos, C.; Dimitriou, V. *Sensor Location Methodology for Improved IEQ Monitoring in Working Environments*; ASHRAE: Atlanta, GA, USA, 2022.


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

buildings

MDPI

*Article*

# How Does the Intelligent Monitoring System Influence the Sense of Security of the Elderly in Home Care? A Case Study of the Hubin Community in Ningde City

**Yan Ma and Wei Xu ***

School of Architecture and Urban-Rural Planning, Fuzhou University, Fuzhou 350108, China
* Correspondence: 211520025@fzu.edu.cn

**Abstract:** Under the background of rapid aging in China, the security of the elderly in home care has become the focus of social attention. The present study takes the Hubin community of Ningde City as the case study area; and uses hierarchical regression analysis, structural equation model, and other methods to explore the influence path of the sense of security of the elderly in home care under the moderating effect of the intelligent monitoring system, and the subjective and objective demands for such equipment among the elderly. The results showed that compared with family care and social support, the influence of individual health on the sense of security of the elderly in home care was dominant. The intelligent monitoring system can play a negative moderating effect in the process of individual health directly affecting the sense of security of the elderly in home care, and indirectly improving the sense of security of the elderly in home care. Therefore, under the premise of paying attention to the individual health of the elderly at home, the reasonable application of the intelligent monitoring system and full play to its moderating effect is a practical way to improve the sense of security of the elderly in home care. In addition, the family and society should also pay more attention to the security of the elderly in home care, so as to promote the overall improvement of their sense of security.

**Keywords:** home care; smart senior care; a sense of security; structural equation model; moderating effect

**Citation:** Ma, Y.; Xu, W. How Does the Intelligent Monitoring System Influence the Sense of Security of the Elderly in Home Care? A Case Study of the Hubin Community in Ningde City. *Buildings* **2023**, *13*, 1255. https://doi.org/10.3390/buildings13051255

Academic Editor: Pierfrancesco De Paola

Received: 10 April 2023
Revised: 2 May 2023
Accepted: 5 May 2023
Published: 10 May 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

At present, China's population is aging rapidly, and China is about to become a deep aging society. In 2021, the population aged 60 and over was 264 million, accounting for 18.7% of the total population. At the same time, the demand for home care services is becoming more and more diversified and personalized, which is the best way for the elderly to choose in China. Although the Chinese government has formulated many public policies and planned many service facilities for the elderly, problems still exist; the imbalance of the supply of and demand for service facilities, poor living environments, and accidents, which have a very negative impact on the sense of security and life satisfaction of the elderly in home care [1].

In view of the above problems, scholars have conducted a lot of research on the demand for services for the elderly, and their life satisfaction and happiness; and on the evaluation and optimization of the spatial configuration of service facilities for the elderly, and elderly-friendly cities and communities. Scholars believe that the demand for elderly services is characterized by differentiation, diversity, and multiple levels, with huge stage differences [2–4]. Scholars believe that economic and social attributes, family care, social support, and living environment have an impact on the life satisfaction and happiness of the elderly [5–8]. In terms of the evaluation and optimization of the spatial configuration of service facilities for the elderly, scholars evaluate the quantity, fairness, accessibility, and other aspects; and put forward some strategies, mainly about selecting

facility location, promoting fairness, and improving block walkability [9–11]. In terms of elderly-friendly cities and communities, scholars have put forward requirements for housing, transportation, outdoor environments, technology, and other aspects [12–14]. At present, artificial intelligence technology is widely used in many areas of residents' daily life. Scholars have begun to study the application of artificial intelligence technology in home care, and some research results have verified that the application of artificial intelligence technology in medical [15], social [16], entertainment [17], safety [18], and other areas can directly or indirectly have a positive impact on the life satisfaction of the elderly. In addition, Tymkiewicz discusses the significance of smart cities for the elderly, and the planning strategy for an elderly-friendly sustainable smart city; and believes that planners should identify the needs of the elderly and work with the community to design the architecture of elderly-friendly and sustainable smart cities [19].

However, there is still a lack of research on security, and the sense of security of the elderly in home care, which is closely related to their quality of life and satisfaction. In China, accidents are one of the main causes of death among the elderly, and falls account for 49.3% of all accidents, most of them occurring at home [20] (p. 15). Due to the high incidence of home care security problems, and the difficultly of helping them in time, many elderly people lack a sense of security in home care. Therefore, research on home care security is of great significance for optimizing the quality of home care services and improving the sense of security and satisfaction of the elderly in home care. Common home care security measures include: home environment with aging-friendly design, third-party home care services, portable emergency help equipment, indoor sensor alarm, etc. [21]. These measures to some extent ensure safety, but are limited by a poor guarantee ability, poor real-time feedback, low convenience, high operating cost, and great difficulty in promotion [22]. The intelligent monitoring system can collect and process video data in real time, and determine—through bone point detection and human posture recognition—whether an elderly person has fallen, and inform the person's family. The intelligent monitoring system can realize the real-time monitoring and timely treatment of accidents such as falls. Compared with traditional safety measures, it has advantages such as a stronger guarantee, better real-time, higher convenience, and lower cost. However, there is a difference between the security of home care, and the feeling of the elderly themselves. Although existing studies have proved that artificial intelligence technology has a positive effect on life satisfaction, the effectiveness and mechanism of improving the sense of security of the elderly in home care still need to be further explored.

The increased aging of the population and the frequent occurrence of home care safety problems make the sense of security of the elderly in home care become a problem that cannot be ignored. However, research on the influence path of the sense of security of the elderly in home care and the mechanism of intelligent devices on the elderly is lacking. Therefore, the purpose of the present study is to explore the influence path of the sense of security of the elderly in home care, the influence mechanism of the intelligent monitoring system on the sense of security of the elderly in home care, and the subjective and objective demands for the intelligent monitoring system of the elderly. On the basis of the results of these analyseis, the present study aims to forward the improvement strategy of home care and the optimization strategy of the intelligent monitoring system. The present study hopes to provide a supplement and reference for the research on the application and effect of artificial intelligence technology in home care and the demand of the elderly for intelligent elderly care services.

## 2. Methods and Data

### *2.1. Research Framework*

The present study constructs a research framework on the influence path of the sense of security of the elderly in home care under the moderating effect of the intelligent monitoring system (Figure 1). Firstly, based on the previous research of the sense of security of the elderly in home care, the present study would construct the influence mechanism

hypothesis. Secondly, the present study would verify the moderating effect of the intelligent monitoring system on the sense of security of the elderly in home care, and then analyze and compare the influence path of the sense of security of the elderly in home care in two cases of whether to install the intelligent monitoring system. Thirdly, the present study would analyze and compare the subjective and objective demands of the intelligent monitoring system of the home elderly. Finally, based on the above analysis, the present study would put forward strategies regarding improving the sense of security of the elderly in home care and optimizing the intelligent monitoring system.

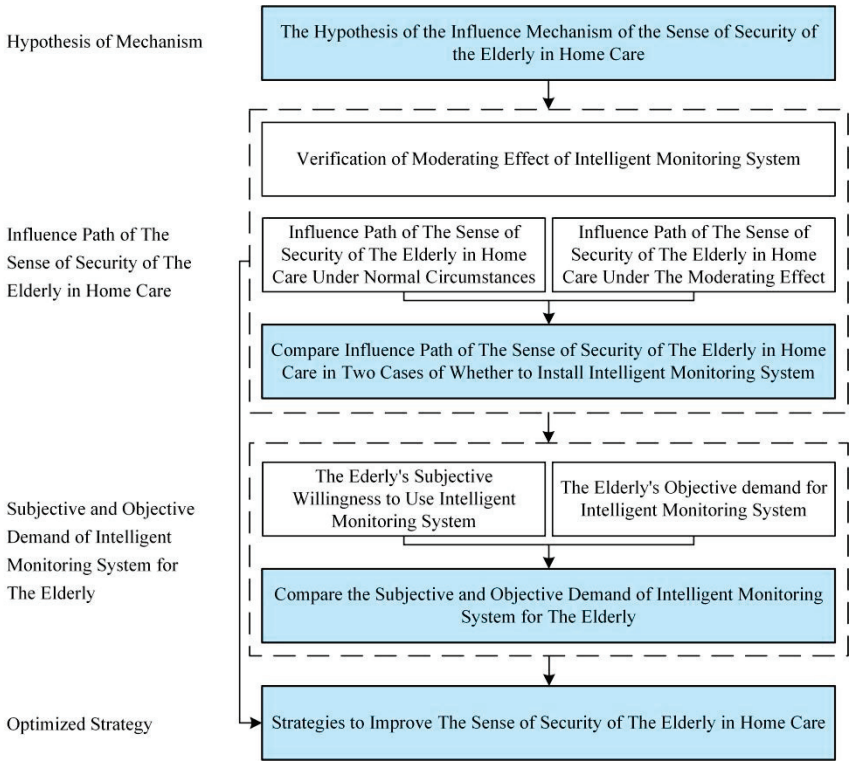



**Figure 1.** Research framework of the influence path of the sense of security of the elderly in home care under the moderating effect of the intelligent monitoring system.

## *2.2. Methods*

### 2.2.1. The Hypothesis of the Influence Mechanism of the Sense of Security of the Elderly in Home Care

Home care is a kind of socialized service with family as the core, community-based and professional services, which mainly focus on solving the difficulties in daily life of the elderly living at home. As a subjective psychological feeling, the sense of security is influenced by many factors, such as the individual himself and the external environment, and these influencing factors are not completely independent, but complex relationships. Maslow's hierarchy of needs believes that safety needs are the next level of demand after physiological needs are met [23], and a sense of security is the most important factor affecting mental health; it is the feeling of eliminating fear and anxiety, making the heart feel safe, confident and free [24]. Previous studies on the sense of security of the elderly have revealed that factors such as individual health [25], family care [26,27], social support [28] and environment can directly affect the sense of security and life satisfaction of the elderly. Living environment factors such as the age-friendliness of the infrastructure [29], acoustic environment [30,31] and poverty environment [32] can also directly or indirectly affect the sense of security and life satisfaction of the elderly. The research object of the present study —— the sense of security of the elderly in home care, emphasizing that the

elderly feel comfortable and stable in daily life in the residence, and avoid excessive worry about accidents.

The external environment of each residential area, and the internal environment of residential buildings in the Hubin community are similar to each other; most of them lack aging design, and the influence of environmental factors on the sense of security of the elderly in home care is not considered. In conclusion, the present study proposed hypotheses about the influencing mechanisms of the sense of security of the elderly in home care (Figure 2). The independent variables are individual health, family care and social support; the dependent variable is the sense of security of the elderly in home care; the moderating variable is intelligent monitoring system. The individual health degree, family care degree, and social support degree of the elderly at home directly affect the sense of security of the elderly in home care. In this process, the intelligent monitoring system can indirectly affect the sense of security of the elderly in home care through the moderating effect.

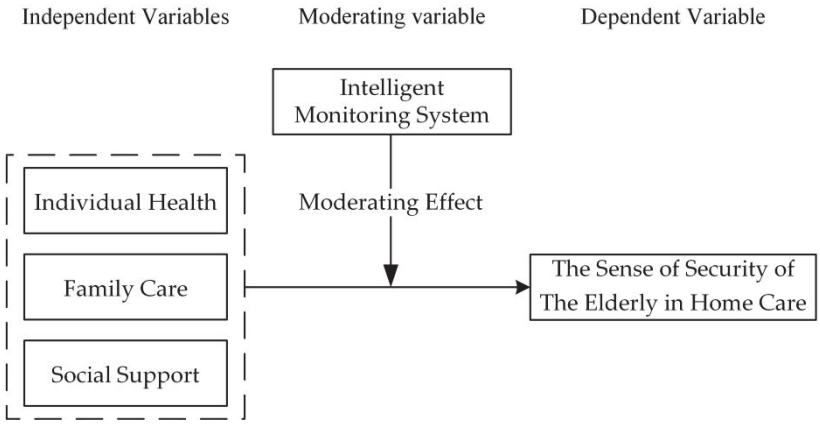



**Figure 2.** Hypotheses about the influencing mechanisms of the sense of security of the elderly in home care.

2.2.2. Validation of the Moderating Effects Based on a Hierarchical Regression Analysis

The moderating effect means that in the process of the influence of the independent variable on the dependent variable, when the moderating variable takes different values, the influence degree of the independent variable on the dependent variable will change significantly. The moderating effect can be expressed by the following formula.

$$Y = aX + bM + cXM + e \quad (1)$$

In Equation (1), X, Y and M are the independent, dependent and moderating variables, respectively. XM is the interaction term of X and M. The interaction term is the product of the independent variable and the moderating variable. a, b and c are the regression coefficients of Y versus X, M and XM, respectively, and e is the error value.

The moderating effect can be verified by a hierarchical regression analysis:

First, the regression analysis of Y to X and M, obtained $R_1^2$;

Second, the regression analysis of Y for X, M and XM, and $R_2^2$, if $R_2^2$ is significantly higher than $R_1^2$, the moderating effect is significant [33].

For example, Tao established hierarchical regression models to analyze the moderating effect of physical activity (PA) between problematic mobile phone use (PMPU) and depression in university students. In this case, PA is the moderator variable, PMPU is the independent variable, and depression is the dependent variable. The results indicate that PA moderates the association between PMPU and depression [34].

2.2.3. Impact Pathway Analysis Based on the Structural Equation Model

Structural equations integrate many methods such as path analysis, regression analysis and factor analysis; and compared with traditional multiple regression analysis, structural equations have certain advantages in the comparison of multi path influence degree and discrimination of multivariate logical relationships. Structural equation models usually include three matrix equations:

$$x = \Lambda_x \xi + \delta \quad (2)$$

$$y = \Lambda_y \eta + \varepsilon \quad (3)$$

$$\eta = B\xi + \Gamma\eta + \zeta \quad (4)$$

Equations (2) and (3) are measurement models, Equation (4) are structural models, x, δ, y and η are exogenous observable variables, exogenous latent variables, endogenous observable variables, and endogenous latent variables, respectively; B and Γ are path coefficients [35].

For example, Long established a structural equation model to examine the interaction between individual psychological factors and contextual city factors related to energy-saving behavior. The case compared the path coefficients of individual psychological factors and urban background factors. The results indicated that energy-saving behavior is mainly influenced by individual psychological factors, while energy-saving promotion behavior is influenced by both individual psychological and contextual city factors [36].

*2.3. Data Source*

2.3.1. Introduction of the Study Area

The present study selected the Hubin community in Ningde City as the case study area for the questionnaire survey and visit. The Hubin community is located in the Dongqiao Economic and Technological Development Zone, Jiaocheng District, covering an area of about 80.75 hectares, and having 9 residential areas under its jurisdiction. Communities with aging rates of more than 10% of have been commonly defined as aging communities [37]. By the end of 2019, the permanent resident population of the Hubin community was about 20,000, among which about 5000 people were over 60 years old, with an aging rate of 25%, which is typical of an aging community. In 2020, the Hubin community built a smart management platform (Figure 3), which has made achievements in smart government affairs, smart property, smart pension and other aspects. The home care service center of the Hubin community has applied the intelligent monitoring system, which has achieved relatively ideal results in the security of the elderly. The pre-survey results show that the community residents have a certain understanding of the intelligent monitoring system. Of the respondents, 58.4% said they had experienced such systems, and 28.3% said they had installed such systems in their homes. Therefore, selecting the Hubin community as the case study area has a good theoretical reference and practical demonstration significance.

2.3.2. Data Procurement

China's Law on the Protection of the Rights and Interests of the Elderly stipulates that all citizens of the People's Republic of China over the age of 60 are the elderly. Since the retirement age of Chinese women is generally 55 years old, the women aged over 55 years old and male residents aged over 60 years old and above were selected as the survey objects. The sample size can be calculated by the following formula:

$$N = z^2 \times p(1-p)/e^2 \quad (5)$$

In Equation (5), N, z, p and e are the minimum sample number, confidence interval, sampling proportion and error value, respectively. In this study, 95% confidence is used, the error range is controlled within 7%, and the z value is 1.96. The minimum sample size N was calculated to be 146.

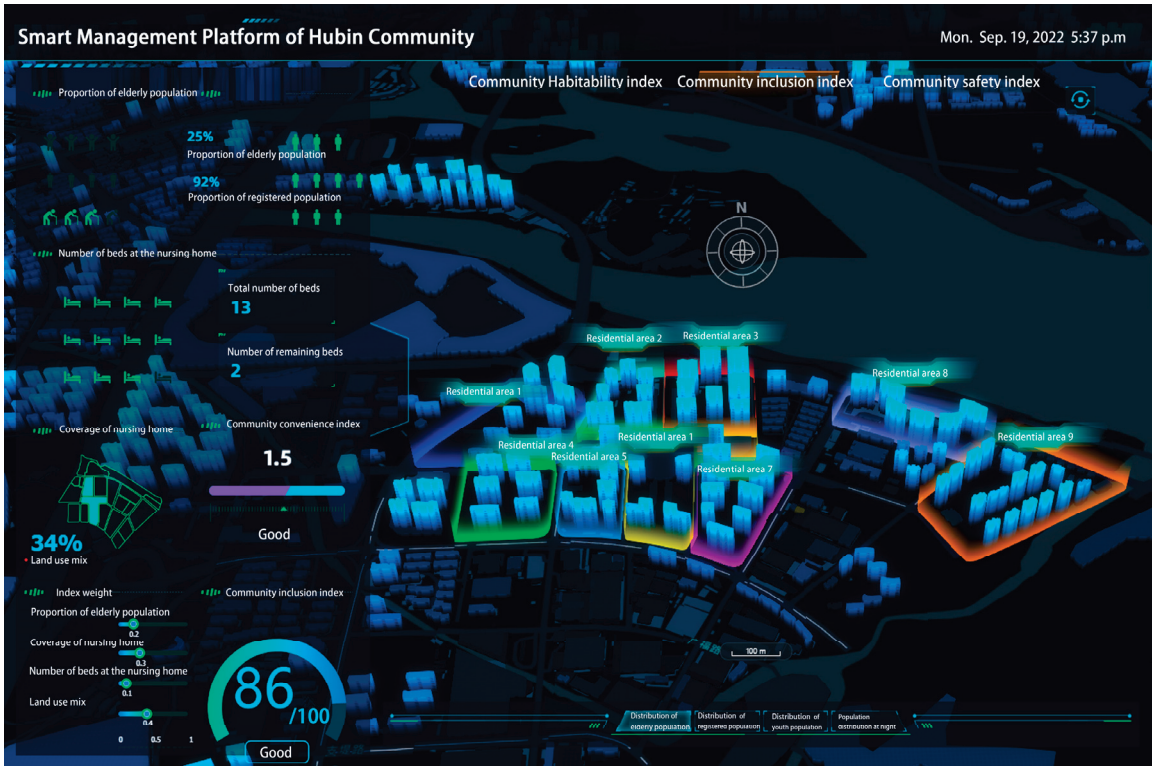



**Figure 3.** Smart management platform of the Hubin community.

In this survey, 200 questionnaires were distributed in the Hubin Community Home Care Service Center, Tianmao City Square, South Bank Park and other places where the elderly gathered, and 166 valid questionnaires were collected, which met the sample size requirement of 95% confidence.

The content of the questionnaire mainly included the respondents' economic and social attributes, the sense of security in home care, the willingness to use the intelligent monitoring system, individual health, family care, social support and other issues. The value and description statistics of each variable in the questionnaire are shown in Table 1.

#### 2.3.3. Reliability of the Sample Data

The reliability test of sample data in statistics mainly includes: the test-retest reliability method, the complex reliability method, the half reliability method and the $\alpha$ reliability coefficient method. Among them, the $\alpha$ reliability coefficient method is the most common method, as follows:

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum S_i^2}{S_t^2}\right) \quad (6)$$

In Equation (6), $\alpha$ is the reliability coefficient; $K$ is the number of test questions, $S_i^2$ is the variance of each subject's score, and $S_t^2$ is the variance of the total scores of all subjects.

To test the reliability of the scale questions involving the sense of security of the elderly in home care, the calculated a coefficient was 0.775, indicating that the questionnaire design had high internal consistency, and the sample data had high representativeness and confidence.

**Table 1.** Variable assignment and description statistics (N = 166).

| Latent Variables | Observable Variables | Variables Assignment | Mean Value | Standard Deviation |
|---|---|---|---|---|
| | Sexual | 1 = Male; 2 = Female | 1.51 | 0.501 |
| | Age | 1 = Age 55–59; 2 = Age 60–69; 3 = Age 70–79; 4 = Age 80 and over | 2.51 | 0.837 |
| | Educational background | 1 = Primary school and below; 2 = Junior middle school; 3 = High School; 4 = College degree; 5 = Graduate degree | 2.07 | 0.902 |
| | Household income | 1 = Less than RMB 50,000/year; 2 = RMB 50,000–100,000/year; 3 = RMB 100,000–150,000/year; 4 = RMB 150,000–200,000/year; 5 = Over than RMB 200,000/year | 3.11 | 1.198 |
| | Have the respondents ever used the intelligent monitoring system? | 1 = No; 2 = Yes | 1.58 | 0.494 |
| | Whether the respondents installed the intelligent monitoring system in their house? | 1 = No; 2 = Yes | 1.28 | 0.452 |
| | Are the respondents willing to use the intelligent monitoring system? | 1 (Very reluctant to)–5 (Very willing to) | 3.19 | 1.258 |
| | Sense of security of the elderly in home care | 1 (Very unsafe)–5 (Very safe) | 3.86 | 1.040 |
| Individual health | Healthy condition | 1 (Very unhealthy)–5 (Very healthy) | 3.68 | 0.934 |
| | Self-care condition | 1 (Unable Self-care)–5 (Fully self-capable) | 3.64 | 0.985 |
| Family care | Living situation | 1 = Live alone; 2 = Live with spouse; 3 = Live with children; 4 = Live with three generations and above | 2.61 | 0.926 |
| | Family relationship | 1 (Very harmonious)–5 (Very harmonious) | 4.14 | 0.916 |
| Social support | Neighborhood relationship | 1 (Very harmonious)–5 (Very harmonious) | 3.29 | 0.991 |
| | Social activities | 1 (No participation at all)–5 (Frequent) | 3.29 | 1.090 |

## 3. Results

### *3.1. Influence Path of the Sense of Security of the Elderly in Home Care*

#### 3.1.1. Verification of Moderating Effect of Intelligent Monitoring System

In the present study, the whole sample is divided into two independent samples according to whether the interviewees installed the intelligent monitoring system. The

sample without the installed intelligent monitoring system is named group 1, and the sample with the installed intelligent monitoring system is named group 2. In order to explore whether and how the intelligent monitoring system affects the sense of security of the elderly in home care, the t-test of two independent samples was analyzed. In order to explore whether and how the intelligent monitoring system affects the security of home care, the average value of the two independent samples was compared. The mean values of home care security in groups 1 and 2 were 3.76 and 4.11, respectively, and the two independent samples had a significant difference of 5% level. It shows that the installation of the intelligent monitoring system can improve the sense of security of the elderly in home care to some extent. However, when the regression analysis on whether the intelligent monitoring system had an impact on the sense of security of the elderly in home care, the significance level of the results was less than 5%. It indicates that whether the intelligent monitoring system is installed or not does not directly affect the sense of security of the elderly in home care, but may indirectly affect the sense of security of home care through the moderating effect.

In order to explore whether there are moderating effects and which process occurs—the hierarchical regression analysis of the independent variable and moderating variable to the dependent variable, as well as of the independent variable, moderating variable and interaction term to the dependent variable—were conducted, respectively. In this analysis, the independent variables are individual health, family care and social support; the dependent variable is the sense of security of the elderly in home care; the moderating variable is whether to install the intelligent monitoring system; and the interaction term is the product of the independent variable and the moderating variable. The calculated results are shown in Table 2.

(1) Individual health

Both health and self-care show 1% significance on the sense of security of the elderly in home care, and the regression coefficient value $B > 0$, indicating that health and self-care have a direct positive effect of 1% on the sense of security of the elderly in home care. $\Delta R^2 > 0$, and $\Delta F$ showed 5% significance, indicating that the moderating effect is significant; while the interaction term showed 5% significance, and the regression coefficient value $B < 0$, indicating that the moderating effect is negative. Therefore, in the process of individual health directly affecting the sense of security of the elderly in home care, the intelligent monitoring system can indirectly affect the sense of home care through the negative moderating effect; that is, it can reduce the impact of individual health on the sense of security of the elderly in home care, so as to indirectly improve the sense of security of the elderly in home care.

(2) Family care

Both the living situation and family relationship showed a significance of 1% on the sense of security of the elderly in home care, and the regression coefficient value $B > 0$, indicating that the living situation and family relationship had a significant direct positive effect of 1% on the sense of security of the elderly in home care. $\Delta F$ is not significant, indicating that the moderating effect of the intelligent monitoring system is not significant in the process of family care directly affecting the sense of security of the elderly in home care.

(3) Social support

Both the neighborhood relationship and social activities showed a significance of 1% on the sense of security of the elderly in home care, and the regression coefficient value $B > 0$, indicating that the living situation and family relationship had a significant direct positive effect of 1% on the sense of security of the elderly in home care. $\Delta F$ is not significant, indicating that the moderating effect of the intelligent monitoring system is not significant in the process of social support directly affecting the sense of security of the elderly in home care.

**Table 2.** Results of hierarchical regression analysis.

| Variable Name | Index | Regression Analysis 1 | Regression Analysis 2 | Index | Regression Analysis 1 | Regression Analysis 2 |
|---|---|---|---|---|---|---|
| | | B | B | | B | B |
| Individual health | Healthy condition | 0.682 ** | 0.778 ** | Self-care condition | 0.768 ** | 0.830 ** |
| | Whether to install Intelligent monitoring system | 0.633 ** | 0.572 ** | Whether to install Intelligent monitoring system | 0.380 ** | 0.375 ** |
| | Healthy condition * Whether to install Intelligent monitoring system | - | −0.341 * | Self-care condition * Whether to install Intelligent monitoring system | - | −0.267 * |
| | $R^2$ | 0.383 | 0.401 | $R^2$ | 0.552 | 0.564 |
| | Adjust $R^2$ | 0.375 | 0.390 | Adjust $R^2$ | 0.547 | 0.555 |
| | F | 50.567 ** | 36.176 ** | F | 100.489 ** | 69.715 ** |
| | $\Delta R^2$ | - | 0.018 | $\Delta R^2$ | - | 0.012 |
| | $\Delta F$ | - | 4.946 * | $\Delta F$ | - | 4.209 * |
| Family care | Living situation | 0.380 ** | 0.395 ** | Family relationship | 0.439 ** | 0.422 |
| | Whether to install Intelligent monitoring system | 0.323 | 0.324 | Whether to install Intelligent monitoring system | 0.269 | 0.262 |
| | Living situation * Whether to install Intelligent monitoring system | - | −0.050 | Family relationship * Whether to install | - | 0.076 |
| | $R^2$ | 0.138 | 0.138 | $R^2$ | 0.171 | 0.172 |
| | Adjust $R^2$ | 0.127 | 0.122 | Adjust $R^2$ | 0.161 | 0.157 |
| | F | 13.008 ** | 8.649 ** | F | 16.854 ** | 11.228 ** |
| | $\Delta R^2$ | - | 0.000 | $\Delta R^2$ | - | 0.001 |
| | $\Delta F$ | - | 0.077 | $\Delta F$ | - | 0.152 |
| Social support | Neighborhood relationship | 0.436 ** | 0.430 ** | Social activities | 0.514 ** | 0.548 ** |
| | Whether to install Intelligent monitoring system | 0.138 | 0.132 | Whether to install Intelligent monitoring system | 0.054 | 0.102 |
| | Neighborhood relationship * Whether to install Intelligent monitoring system | - | 0.026 | Social activities * Whether to install Intelligent monitoring system | - | −0.165 |
| | $R^2$ | 0.187 | 0.187 | $R^2$ | 0.297 | 0.302 |
| | Adjust $R^2$ | 0.177 | 0.172 | Adjust $R^2$ | 0.289 | 0.289 |
| | F | 18.773 ** | 12.448 ** | F | 34.482 ** | 23.354 ** |
| | $\Delta R^2$ | - | 0.000 | $\Delta R^2$ | - | 0.005 |
| | $\Delta F$ | - | 0.022 | $\Delta F$ | - | 1.068 |

** and * are significant at 1% and 5% levels, respectively.

In order to more intuitively show the intelligent monitoring system for the moderating effect on the sense of security of the elderly in home care, two cases, namely the intelligent

monitoring system installed and not installed, and individual health on influencing the sense of security of the elderly in home care are compared; with the health and self-care situations as independent variables, and the sense of security of the elderly in home care as the dependent variable, we draw the slope analysis diagram (Figure 4).

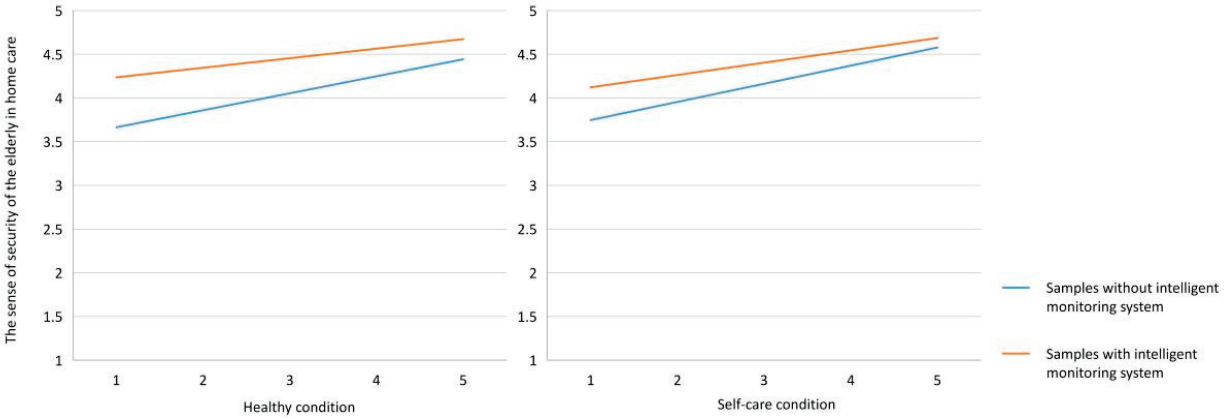



**Figure 4.** Analysis of the slope of the moderating effects.

The results show that in the process of the health situation and self-care situation influencing the sense of security of the elderly in home care, compared with the samples without the intelligent monitoring system, the samples with the intelligent monitoring system have a higher the sense of security and a lower slope. This result once again verifies that the intelligent monitoring system can play a negative moderating effect in the process of individual health directly affecting the sense of security of the elderly in home care. In the sense of security of the elderly in home care, the difference between the samples of whether to install the intelligent monitoring system gradually decreases with the improvement of health conditions and self-care conditions. In short, the lower the health and self-care situation of the elderly at home, the more obvious the moderating effect of the intelligent monitoring system on the sense of security of the elderly in home care; that is, the intelligent monitoring system has the stronger indirect improvement effect on the sense of security in home care of the elderly with low health.

3.1.2. Analysis of the Influence Path of the Sense of Security of the Elderly in Home Care

Based on the data of group 1 and group 2, we use AMOS to construct the structural equation model 1 and model 2 for the sense of security of the elderly in home care. We use CMIN/DF, RMSEA, and CFI to assess the fit of models 1 and 2. The fitting evaluation results (Table 3) indicate that model 1 and model 2 fit well overall, with high representativeness and confidence. The results of structural equation model analysis is shown in Figure 5.

The result of model 1 analysis shows that in the normal case without the installed intelligent monitoring system, individual health, family care and social support have significant direct positive impacts on the sense of security of the elderly in home care, among which the direct positive impact of individual health on the sense of security of the elderly in home care is dominant. The theoretical reason may be that in Maslow's hierarchy of needs, the satisfaction of physiological needs is the premise of safety needs, which can provide strong support for the safety needs, while love and belonging needs have a relatively weak effect on the safety needs. The practical reason may be that the elderly who choose home care have relatively good health and self-care conditions, and can obtain a sufficient sense of security by themselves, and obtain a relatively lesser sense of security in the outside world. In addition, individual health has a significant positive impact on social care by 5%, which can also be understood that when individual health directly affects the sense of security of the elderly in home care, it can indirectly affect the sense of security of the elderly in home care through some intermediary effect. The reason

may be that the elderly with better health and self-care conditions are more able to handle neighborhood relationships and participate in social activities.

**Table 3.** Goodness-of-fit statistics of the model and reference values.

| Fits Index | Reference Value | Model 1 | Model 2 |
|---|---|---|---|
| CMIN/DF | <3.00 | 1.164 | 1.367 |
| RMSEA | <0.10 | 0.037 | 0.089 |
| CFI | >0.90 | 0.995 | 0.972 |

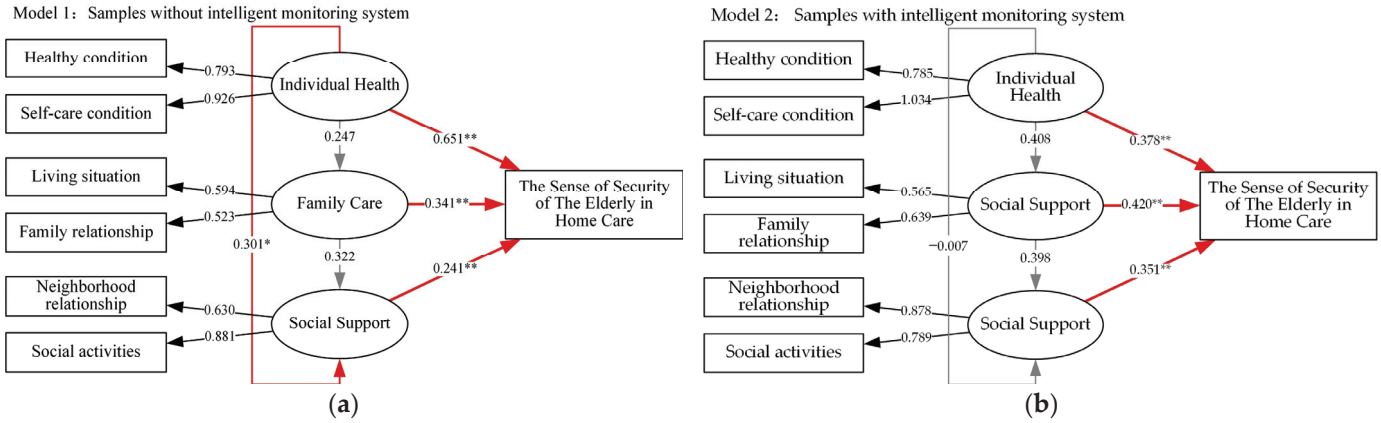



**Figure 5.** Results of the structural equation model analysis: (**a**) Analysis results of Model 1; (**b**) Analysis results of Model 2. Rectangles are the observable variables, and ellipses are the latent variables. The red, blue, and gray arrows indicate significant positive, significant negative and insignificant effects, respectively. The values next to the arrows are standardized regression coefficients. ** and * are significant at 1% and 5% levels, respectively.

The result of model 2 analysis shows that under the moderating effect of the intelligent monitoring system, individual health, family care and social support still have a significant direct positive effect of 1% on the sense of security of the elderly in home care. However, the influence of individual health on the sense of security of the elderly in home care is significantly reduced, and the influence of family care and social support on the security of home care is significantly improved. Family care has become the primary factor affecting the sense of security of the elderly in home care.

### *3.2. The Subjective and Objective Demand for the Intelligent Monitoring System of the Elderly*

#### 3.2.1. The Subjective Willingness to Use the Intelligent Monitoring System of Elderly

The present study investigated the subjective willingness of the elderly to use the intelligent monitoring system; frequency distribution statistical results (Figure 6) show that more than 40% of the elderly are willing or very willing to use the intelligent monitoring system, a few elderly show general use intention, and nearly 30% of the elderly are unwilling or very reluctant to use the intelligent monitoring system.

In order to explore what factors can affect the elderly's subjective willingness to use the intelligent monitoring system, the present study conducted a linear regression analysis of the various economic and social attributes of the elderly. Results (Table 4) show that the factors which affect the subjective willingness of the elderly to use the intelligent monitoring system include age, educational background, household income, health condition, living situation, and social activities. Among them, the positive effect of elderly educational background on subjective intention to use was significant, at the 5% level; the positive effect of elderly household income on subjective intention to use was significant at the 1% level; the negative effect of elderly health condition on subjective intention to use was significant, at the 1% level; and the positive effect of elderly living situation and social activities on subjective intention to use was significant, at the 5% level.

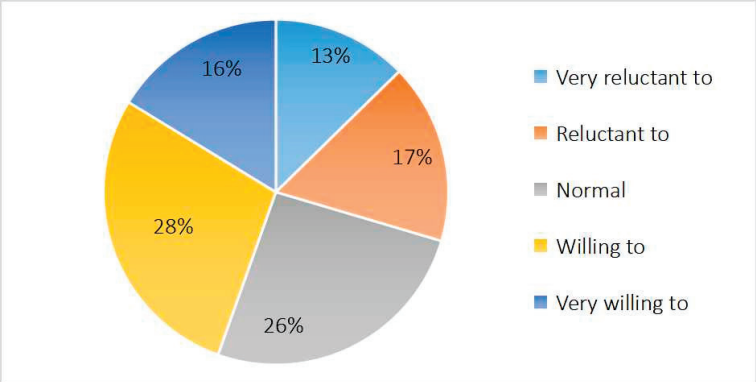



**Figure 6.** The subjective willingness of the elderly to use the intelligent monitoring system.

**Table 4.** Regression analysis of the influencing factors.

| Index | Sexual | Age | Educational Background | Household Income | Health Condition |
|---|---|---|---|---|---|
| B | −0.205 | −0.450 ** | 0.247 * | 0.312 ** | −0.594 ** |
| t | −1.202 | −4.059 | 2.391 | 4.182 | −4.245 |
| **Index** | **Self-Care Condition** | **Living Situation** | **Family Relationship** | **Neighborhood Relationship** | **Social Activities** |
| B | 0.171 | −0.195 * | 0.155 | 0.118 | −0.217 * |
| t | 1.299 | −2.044 | 1.604 | 1.109 | −2.178 |

** and * are significant at 1% and 5% levels, respectively.

Through interviews, the present study found that the reasons may be that age under 69 and highly educated elderly have a higher acceptance of new things, and high-income elderly are more willing to consume technology products. Thus, these two elderly groups are more willing to use intelligent monitoring systems. The elderly in better health are more optimistic about their self-security ability; the elderly who live with family descendants can fully receive their safe care; and the elderly who often participate in social activities are more likely to get help from their neighbors. These three types of elderly can be guaranteed from three aspects of individual health, family care and social support; their levels of the sense of security is relatively high. Thus, they are even more reluctant to use the intelligent monitoring system.

#### 3.2.2. The Objective Demand for the Intelligent Monitoring System of the Elderly

Based on the China country assessment report on ageing and health [20] (p. 7), the influence path of the sense of security of the elderly in home care, and the questionnaire survey and interview of some family members of the elderly, the present study identified the objective needs of the elderly for the intelligent monitoring system.

According to the China country assessment report on ageing and health, the elderly and the elderly with poor health and self-care conditions are more dependent on the care of others. The influence path of the sense of security of the elderly in home care shows that elderly individuals living alone can obtain insufficient family care, and have a high risk of accidents such as falls. The statistical results of the willingness of the family members of the elderly to use the intelligent monitoring system (Figure 7) show that the intention of the elderly family members to use the intelligent monitoring system is slightly higher than the subjective intention of the elderly. Factors that influence the decisions of family members of elderly to install intelligent monitoring systems include age, living situation, health condition and self-care condition. For the elderly aged over 69, and who live alone or live with their spouses and have poor health and self-care conditions, their family members are more willing to install intelligent monitoring systems. In short, it can be considered

that the elderly who are aged over 69, have poor health and self-care conditions, and livie alone objectively need the intelligent monitoring system to ensure the safety of home care and enhance the sense of security of the elderly in home care.

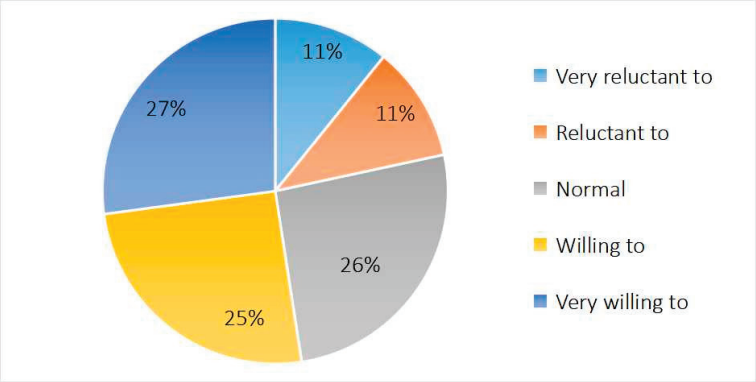



**Figure 7.** The objective demand for the intelligent monitoring system of the elderly.

Comparing the subjective and objective demands of the elderly for the intelligent monitoring system, it is found that although the elderly aged over 69 need to install the intelligent monitoring system more objectively, their subjective willingness to use it is not high. Through interview, the present study found that the reasons include two points. First, some elderly aged over 69 who live with family descendants who can fully obtain their safety care may think it is not necessary to use the intelligent monitoring system. Second, some elderly aged over 69 do not understand enough about the intelligent monitoring system, and worry about personal privacy leakage, high cost, telecommunication fraud, electronic radiation and other problems, so they are unwilling to install the intelligent monitoring system at home.

## 4. Discussion and Conclusions

Frequent family accidents in the elderly have a very negative impact on the sense of security and happiness of the elderly. The present study takes the Hubin community in Ningde City as the case study area, uses hierarchical regression analysis, structural equation modeling and other methods to explore the influence path of the sense of security of the elderly in home care, the influence mechanism of the intelligent monitoring system on the sense of security of the elderly in home care, and the subjective and objective demand of the elderly for the intelligent monitoring system. The following conclusions have been drawn:

- In terms of the influence path of the sense of security of the elderly in home care, individual health, family care and social support of the elderly have significant direct positive effects on the sense of security of home care. In the routine case without the installed intelligent monitoring system, the influence of individual health on the sense of security of the elderly in home care is dominant;
- In terms of the influence mechanism of the intelligent monitoring system on the sense of security of the elderly in home care, in the process of individual health directly affecting the sense of security of the elderly in home care, the intelligent monitoring system can play a negative moderating effect and indirectly improve the sense of security of the elderly in home care. Under the moderating effect of the intelligent monitoring system, the influence of individual health on the sense of security of the elderly in home care is significantly reduced, and the degree of family care becomes the primary factor affecting the sense of security of the elderly in home care;
- In terms of the subjective and objective demand of the elderly for the intelligent monitoring system, the elderly aged over 69, who have poor health and self-care conditions, living alone, objectively need the intelligent monitoring system. Although most of the elderly are willing to use the intelligent monitoring system, some elderly

aged over 69 show low subjective willingness to use it due to their low understanding and acceptance of new things, which deviates from the objective demand.

Based on the above conclusions, the following practice recommendations have been made regarding improving the sense of security of the elderly in home care and optimizing the intelligent monitoring system:

- In terms of improving the sense of security of the elderly in home care, the elderly or their family members can install the intelligent monitoring system at home to ensure the safety of the elderly at home and improve their sense of security. Family members and community workers should pay more attention to the safety of the elderly in home care, especially to the safety of elderly people over 69 years and living alone;
- In terms of optimizing and promoting the intelligent monitoring system, research and development personnel can improve the intelligent monitoring system from the aspects of network security and product price, so that the elderly groups who objectively need such equipment are subjectively willing to use it. City and community managers should more extensively carry out the construction of smart elderly care in aging communities, and install intelligent monitoring systems in public places such as elderly activity centers and community elderly day care centers for the elderly, so as to add an intelligent guarantee for the security of the elderly in home care;
- In terms of the design of elderly-friendly smart cities and communities, planners should understand the service needs of the elderly, evaluate their willingness and ability to use smart devices, analyze the effectiveness of smart devices to help the elderly, and then carry out elderly-friendly design of smart devices, so that the elderly can better enjoy the convenience brought by smart cities.

The application and influence of artificial intelligence technology in home care is a subject worthy of further research. To some extent, the present study provides ideas for the research on the application and effect of artificial intelligence technology in home care, and the demand of the elderly for intelligent elderly care services. The research is of reference significance for the construction of an intelligent elderly care service system and elderly-friendly smart city and community planning.

The present study focuses in-depth on the Hubin community of Ningde City. The coverage of the questionnaire is relatively limited, and the sample of the intelligent monitoring system installed is relatively insufficient. In future studies, the questionnaires can be expanded, and different types of aging communities can be studied. When studying the influence path of the sense of security of the elderly in home care, and the subjective willingness to use the intelligent monitoring system of the elderly, the present study used the structural equation model and linear regression to analyze linear effects, while complex effects on non-linear effects are under-considered. In future studies, the methods can be further improved to reveal the non-linear effects in depth.

With the continuous promotion of the construction of smart communities and smart elderly care, the application of artificial intelligence technology in various life scenarios such as catering, shopping and transportation for the elderly can also be further studied. Artificial intelligence technology can better serve the multi-level and differentiated needs of the elderly, and comprehensively improve the quality of home care services.

**Author Contributions:** Conceptualization, Y.M. and W.X.; methodology, Y.M. and W.X; validation, Y.M.; formal analysis, W.X.; investigation, W.X.; resources, Y.M.; data curation, W.X.; writing—original draft preparation, W.X.; writing—review and editing, Y.M. and W.X. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China (52008112).

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author W.X., upon reasonable request.

**Conflicts of Interest:** The author declares no conflict of interest.

## References


1. Gao, X.; Wu, D.; Xu, Z.; Yan, B. A Review and Frame-Work Setting of Geographical Research on Aging in China. *Prog. Geogr.* **2015**, *12*, 1480–1494.
2. Maryam, N.; Mohsen, F. Temporary Reuse in Leftover Spaces Through the Preferences of the Elderly. *Cities* **2022**, *127*, 103769. [CrossRef]
3. Esther, H.K.Y.; Sheila, C.; Edwin, H.W.C. Social needs of the elderly and active aging in public open spaces in urban renewal. *Cities* **2016**, *52*, 114–122. [CrossRef]
4. He, J.; Zhou, D.; Dai, J. Study on Evaluation System of Urban Elderly Living Related Facilities Based on Demand Theories. *Archit. J.* **2020**, *S2*, 37–44.
5. Jana, T.; Nina, D. Residential Satisfaction of Elderly in the City Centre: The Case of Revitalizing Neighborhoods in Prague. *Cities* **2012**, *5*, 310–317. [CrossRef]
6. Yan, B.; Gao, X. Home Care Satisfaction Analysis of Aging Urban Chinese Populations: Potential Factors and Community Difference Analysis. *Geogr. Res.* **2013**, *7*, 1269–1279.
7. Gabriele, P. Correlates of quality of life, happiness and life satisfaction among European adults older than 50 years: A machine-learning approach. *Arch. Gerontol. Geriatr.* **2022**, *103*, 104791. [CrossRef]
8. Envelope, J.; Envelope, S.; Envelope, Y. Can Social Capital Improve the Quality of Life Satisfaction for Older Adults? Focusing on the 2016 Quality of Life Survey in Gyeonggi Province, Korea. *Cities* **2022**, *130*, 103853. [CrossRef]
9. Ting, X.; Kun, S. Research on Home-Based Community Care for the Elderly and Index of Elderly Facility in Community. *City Plan. Rev.* **2016**, *8*, 71–76.
10. Wan, D.; Liu, H.; Guo, J.; Guo, L.; Qi, D.; Zhang, S.; Li, P.; Fukuda, H. Spatial Distribution and Accessibility Measurements for Elderly Day Care Centers in China's Urban Built-up Area: The Case of Tianjin Nankai District. *Buildings* **2022**, *12*, 1413. [CrossRef]
11. Gong, N.; Meng, Y.; Hu, Q.; Du, Q.; Wu, X.; Zou, W.; Zhu, M.; Chen, J.; Zhang, M.; Luo, L.; et al. Obstacles to Access to Community Care in Urban Senior-Only Households: A Qualitative Study. *BMC Geriatr.* **2022**, *22*, 122. [CrossRef] [PubMed]
12. Steels, S. Key characteristics of age-friendly cities and communities: A review. *Cities* **2015**, *47*, 45–52. [CrossRef]
13. Chen, Q.; Zhang, Z.; Mao, Y.; Deng, R.; Shui, Y.; Wang, K.; Hu, Y. Investigating the Influence of Age-Friendly Community Infrastructure Facilities on the Health of the Elderly in China. *Buildings* **2023**, *13*, 341. [CrossRef]
14. Shi, J.; Liu, X.; Feng, Z. Age-friendly cities and communities and cognitive health among Chinese older adults: Evidence from the China Health and Retirement Longitudinal Studies. *Cities* **2023**, *132*, 104072. [CrossRef]
15. Park, M.; Bui, L.K.; Jeong, M.; Choi, E.J.; Lee, N.; Kwak, M.; Kim, J.; Kim, J.; Jung, J.; Guk, H.; et al. ICT-based Person-Centered Community Care Platform (IPC3P) to Enhance Shared Decision-making for Integrated Health and Social Care Services. *Int. J. Med. Inform.* **2021**, *156*, 104590. [CrossRef] [PubMed]
16. Hui, C.; Feng, Z. Impact of ICT on Community Satisfaction Among Elderly: The Case of Suojin Community in Nanjing City. *Prog. Geogr.* **2016**, *9*, 1167–1176.
17. He, N.; Huo, C.; Xu, G.; Ping, H.; Zhang, T.; Li, Z. The Effectof Artificial Intelligence Application on the Quality of Elderly Care—Evidence from Survey Data in Hangzhou, Hefei and Wuhan. *Soc. Secur. Stud.* **2021**, *78*, 72–80.
18. Trzpiot, G.; Szołtysek, J. *Safety of the Elderly in Smart City*; Research Papers of Wrocław University of Economics nr 483; Publishing House of Wrocław University of Economics: Wrocław, Poland, 2017.
19. Tymkiewicz, J. The Role of an Architect in Creating the Image of an Elderly-Friendly Sustainable Smart City. *Buildings* **2019**, *9*, 223. [CrossRef]
20. World Health Organization. *China Country Assessment Report on Ageing and Health*; World Health Organization: Geneva, Switzerland, 2015; pp. 12–17.
21. He, C.; Liu, S.; Zhong, G.; Wu, H.; Cheng, L.; Lin, J.; Huang, Q. A Non-Contact Fall Detection Method for Bathroom Application Based on MEMS Infrared Sensors. *Micromachines* **2023**, *14*, 130. [CrossRef] [PubMed]
22. Liu, L.; Zhang, H. The Assessment and Prevention of Falls Among Old People. *Med. Recapitul.* **2007**, *11*, 868–870.
23. Kim, B.R.; Hwang, H.H. Analysis of Major Factors Affecting the Quality of Life of the Elderly in Korea in Preparation for a Super-Aged Society. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9618. [CrossRef] [PubMed]
24. Luo, Y.; Wu, X.; Liao, L.; Zou, H.; Zhang, L. Children's Filial Piety Changes Life Satisfaction of the Left-Behind Elderly in Rural Areas in China? *Int. J. Environ. Res. Public Health* **2022**, *19*, 4658. [CrossRef]
25. Zhang, W.; Li, S. The influence of children's intergenerational support behavior on life satisfaction among rural elderly people. *Popul. Res.* **2005**, *5*, 73–80.
26. Li, J. Study on the relationship between quality of life and social support in elderly population. *Popul. Res.* **2007**, *3*, 50–60.
27. Antonides, G. Motivation and Personality. In *Psychology in Economics and Business*; Springer: Dordrecht, The Netherlands, 1991. [CrossRef]
28. Maslow, A.H. The Dynamics of Psychological Security-Insecurity. *Character Personal.* **1942**, *10*, 331–344. [CrossRef]
29. Zhang, J.; Liu, H.; Qi, Y.; Li, X. Living Environment and Life Satisfaction of Aged Population in Beijing Municipality. *Prog. Geogr.* **2015**, *12*, 1628–1636.
30. Guo, L.-H.; Cheng, S.; Liu, J.; Wang, Y.; Cai, Y.; Hong, X.-C. Does social perception data express the spatio-temporal pattern of perceived urban noise? A case study based on 3137 noise complaints in Fuzhou, China. *Appl. Acoust.* **2022**, *201*, 109129. [CrossRef]

31. Hong, X.-C.; Cheng, S.; Liu, J.; Dang, E.; Wang, J.-B.; Cheng, Y. The Physiological Restorative Role of Soundscape in Different Forest Structures. *Forests* **2022**, *13*, 1920. [CrossRef]
32. Valerie, B. The effects of poverty environments on elders' subjective well-being a conceptual model. *Gerontologist* **1995**, *35*, 541–548. [CrossRef]
33. Sang-June, P.; Youjae, Y. Decomposing Main Effects in Moderated Regression Models. *J. Bus. Res.* **2023**, *157*, 113577. [CrossRef]
34. Tao, S.; Wu, X.; Yang, Y.; Tao, F. The moderating effect of physical activity in the relation between problematic mobile phone use and depression among university students. *J. Affect. Disord.* **2020**, *273*, 167–172. [CrossRef]
35. Otis, D.D. *Introduction to Structural Equation Models*; Academic Press: Cambridge, MA, USA, 1975; pp. 9–24. [CrossRef]
36. Long, R.; Wang, J.; Chen, H.; Li, Q.; Wu, M.; Tan-Soo, J.S. Applying multilevel structural equation modeling to energy-saving behavior: The interaction of individual- and city-level factors. *Energy Policy* **2023**, *174*, 113423. [CrossRef]
37. Bo, X.; Wei, W.; Jie, Z. Senior community space evaluation and planning. *Planners* **2015**, *31*, 5–11+33.


**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

buildings

MDPI

*Article*

# Urban Residents' Preferred Walking Street Setting and Environmental Factors: The Case of Chengdu City

**Qian Yan [1], Shixian Luo [2,*] and Jiayi Jiang [3,4]**

[1] School of Landscape Architecture, Beijing Forestry University, Beijing 100083, China; yanqian603@126.com
[2] School of Architecture, Southwest Jiaotong University, Chengdu 611756, China
[3] School of Architecture, Soochow University, Suzhou 215123, China; jyjiang@suda.edu.cn
[4] China-Portugal Joint Laboratory of Cultural Heritage Conservations Science Supported by the Belt and Road Initiative, Suzhou 215123, China
* Correspondence: shixianluo@yahoo.com; Tel.: +86-18108082672

**Abstract:** To date, most studies on building environments and walking behavior have utilized top-down approaches (e.g., big data or social media data) yet lack bottom-up approaches to verify their findings. Therefore, this study divided urban streets into three main settings (community streets, waterfront paths, and urban greenways) and collected data from a sample of 411 urban residents in Chengdu via an online questionnaire to examine the impact of street environmental factors on their choice of walking path. It was found that: (1) people with higher levels of education preferred streets with water bodies as walking paths; (2) the environmental quality of the physical and aesthetic aspects both had an impact on residents' choices, and the aesthetic environmental quality had a stronger impact; (3) the impact of most infrastructures on community streets was stronger than on other streets; (4) residents were more concerned about the environmental quality of waterfront paths and urban greenways. Based on these findings, three design patterns for residents' preferred street environments are proposed.

**Keywords:** walking streets; build environments; environmental factors; physical environmental factors; aesthetic environmental factors; preferred path; street design; online questionnaire; bottom-up approach

**Citation:** Yan, Q.; Luo, S.; Jiang, J. Urban Residents' Preferred Walking Street Setting and Environmental Factors: The Case of Chengdu City. *Buildings* **2023**, *13*, 1199. https://doi.org/10.3390/buildings13051199

Academic Editors: Guangyu Wang, Jiang Liu, Xin-Chen Hong, Jinda Qi, Bao-Jie He and Shi Cheng

Received: 31 March 2023
Revised: 24 April 2023
Accepted: 25 April 2023
Published: 30 April 2023

**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

## 1. Introduction

### *1.1. Importance of the Built Environment*

By 2030, the urban population will have grown due to rapid urbanization. The influx of a large number of people into urban areas has resulted in worsening congestion and substandard living conditions. Owing to the high population density and lack of public facilities, residents in cities could experience various mental and physical health issues. Hence, addressing the health concerns of urban residents has become a global challenge for cities [1].

The built environment, as the most common and active area for residents [2,3], is defined as part of the physical environment that is constructed by human activity [4]. Therefore, it is considered to significantly influence the travel habits of urban residents [2,3]. In addition to providing space for simple daily travel, the built environment accommodates a variety of social activities [5]. The overall attractiveness and safety of the built environment encourage residents to be more physically active, thereby increasing opportunities for physical activity and social interaction. Accordingly, well-designed urban built environments can reduce the risk of disease among residents. A comprehensive definition of health is "health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" [6]. In addition, a pleasantly built environment may affect pedestrian behavior by increasing the frequency of outdoor activities, which has positive psychological and physical health effects [7]. Consequently, as an essential component of cities, a well-designed built environment can enhance the residents' quality of life.

Furthermore, the built environment, especially the neighborhood street environment, plays an important role in influencing the health of urban residents. Studies at the neighborhood level have observed the subjective impacts of streets on residents. In addition to the impact of the built environment on residents' walking preferences for basic travel, the street environment can also influence residents' outdoor recreational behaviors, such as walking [8,9]. The relationship between the built environment and walking behavior has been the subject of numerous studies in recent years [10–13].

### *1.2. Value of Walking Behavior for Public Health*

Walking is one of the most accessible forms of physical activity [14] and can readily contribute to the population's physical health. Through a review of prior research, walking can reduce the likelihood of cardiovascular disease, certain cancers, type 2 diabetes, osteoarthritis, and osteoporosis, the risk of death from cardiovascular disease and cancer [15], injury, improves bone strength, accelerates metabolism, controls blood pressure, and enhances the mental health of pedestrians [16–18]. Walking can also maintain long-term weight loss as well as increase social confidence [19,20].

Additionally, walking has a positive effect on the mental health of a population. It can reduce blood pressure, symptoms of depression and anxiety [21], and perceived stress. It can also improve cognitive health [22], concentration, and social cohesion [23]. Consequently, walking can improve both the physical and mental health of residents, making the enhancement of urban public health extremely valuable.

### *1.3. Effect of Street Environmental Quality on Walking Behavior*

A well-designed street can enhance residents' quality of life and encourage walking, thereby improving their physical and mental health. Measuring the quality of a street and designing one that is aesthetically pleasing has become a significant area of study. In general, the quality of an environment can be described in terms of objective physical environmental quality and subjective aesthetic environmental quality.

The physical environmental quality of a street (such as infrastructure and walking conditions) influences the probability that residents will utilize it as a pedestrian space. Previous research has indicated that the provision of infrastructure increases street walkability [24–26]. When determining walking route options, infrastructure data frequently include parks, restaurants, cafes, stores, medical services, and recreational facilities [27]. In addition, the walking conditions of streets affect residents' walking, and previous studies have found that diverse neighborhoods well-served by public transportation have higher levels of walking activity [28–30]. Sidewalk width also influences pedestrian path preferences, while the number of roadway intersections, the number of rising steps, and the presence of crosswalks or overpasses impact residents' walking preferences [31–34]. Moreover, the environmental quality of the street can also impact residents' walking preferences, and the presence of street items such as fountains, public art installations, public furniture, and green spaces can increase the appeal of a street to pedestrians [35–37].

The aesthetic quality of streets has long been discussed in terms of the nature of beauty, which Baumgarten formalized in the 18th century under the term "aesthetics". Around this time, people began philosophizing about the human sense of beauty. Modern design is not only concerned with aesthetic qualities but also with aesthetic perception [38]. Some studies have found a positive correlation between walking and perceptions of attractiveness, aesthetics, and greenery [39–41]. Street aesthetics shape urban design qualities (such as imageability, closure, human scale, and transparency), which affect walkability by eliciting individual responses (such as feelings of safety, comfort, and interest) [42]. In addition, Koo et al. (2022) examined the relationships between harmony, rhythm, balance, order, complexity, scale, maintenance, and pedestrians on streets [43]. Zhao et al. (2018) discovered that the soundscape and olfactory characteristics of the environment influence pedestrian perception [44–47]. Accordingly, this study aimed to investigate and

discuss the reasons why urban residents choose a particular street for walking based on two dimensions: physical quality and aesthetic quality.

### *1.4. Research Questions*

Alan Jacobs was the first to propose a path survey methodology for pedestrian streets. Later, Montello et al. gathered data on urban streets and pedestrian perceptions via field surveys, interviews, and questionnaires [48]. Gradually, quantitative methods, such as stated preference surveys, have been incorporated into field surveys, frequently employing manually collected small data sets. Despite numerous studies addressing the influence of the street environment on residential walking activity, the majority of studies on path behavior preferences have relied on top-down analyses that combine path information derived from large data sets with an urban context [49,50]. It is essential to note that top-down studies are typically valid; however, validating their accuracy is difficult because most conclusions are based on speculation from numerical results. More bottom-up studies (such as questionnaires) are required to directly validate the influence of each environmental element on path selection.

In addition, the concept of "street" has been rather vague in many recent studies. Zhong et al. (2022) identified three types of streets: "urban sidewalks," "community sidewalks," and "green space sidewalks," and discovered that the three distinct street environments had different impacts on people and that various environmental elements have different positive and negative impacts on residents [51]. Hence, to apply these findings to specific street types, as in Zhang et al. (2022), we first categorized urban streets into three types: community streets (built environment), waterfront paths (built environment with water elements), and urban greenways (built environment with green elements) [51]. Using a questionnaire, this study attempted to answer the following key questions:

1. What kind of street setting do different people prefer as a walking path?
2. Which physical characteristics influence the selection of preferred walking streets based on the street environment?
3. Depending on the street environment, which aesthetic qualities influence residents' choice of preferred walking streets?

## 2. Materials and Methods

### *2.1. Research Area*

This study was conducted in Chengdu, Sichuan Province, China (Figure 1). The urban area has a population of 9.52 million (2019). Chengdu adopted the "Internationalized Community Construction Plan (2018–2022)" and "Internationalized Community Construction Policy Measures" (http://www.cdswszw.gov.cn/zcfg/Detail.aspx?id=5930, accessed on 29 May 2019), with the objective of creating a high-quality, harmonious, and livable community, aiming to create more comfortable and convenient urban street spaces for residents of Chengdu's central city. The Chengdu Municipal Government proposed the "Livable Chengdu" concept in 2022, aiming to improve the "walkability" of urban streets and encourage more residents to use them for outdoor recreation. As a result, a design strategy to improve city streets has become one of the city's most important policies.

### *2.2. Questionnaire Design*

The authors designed a series of questions regarding walking in urban streets and collected data from a sample of urban residents. Owing to the cost of the study and the limitations of the COVID-19 pandemic, we collected data via online survey platforms and social media.

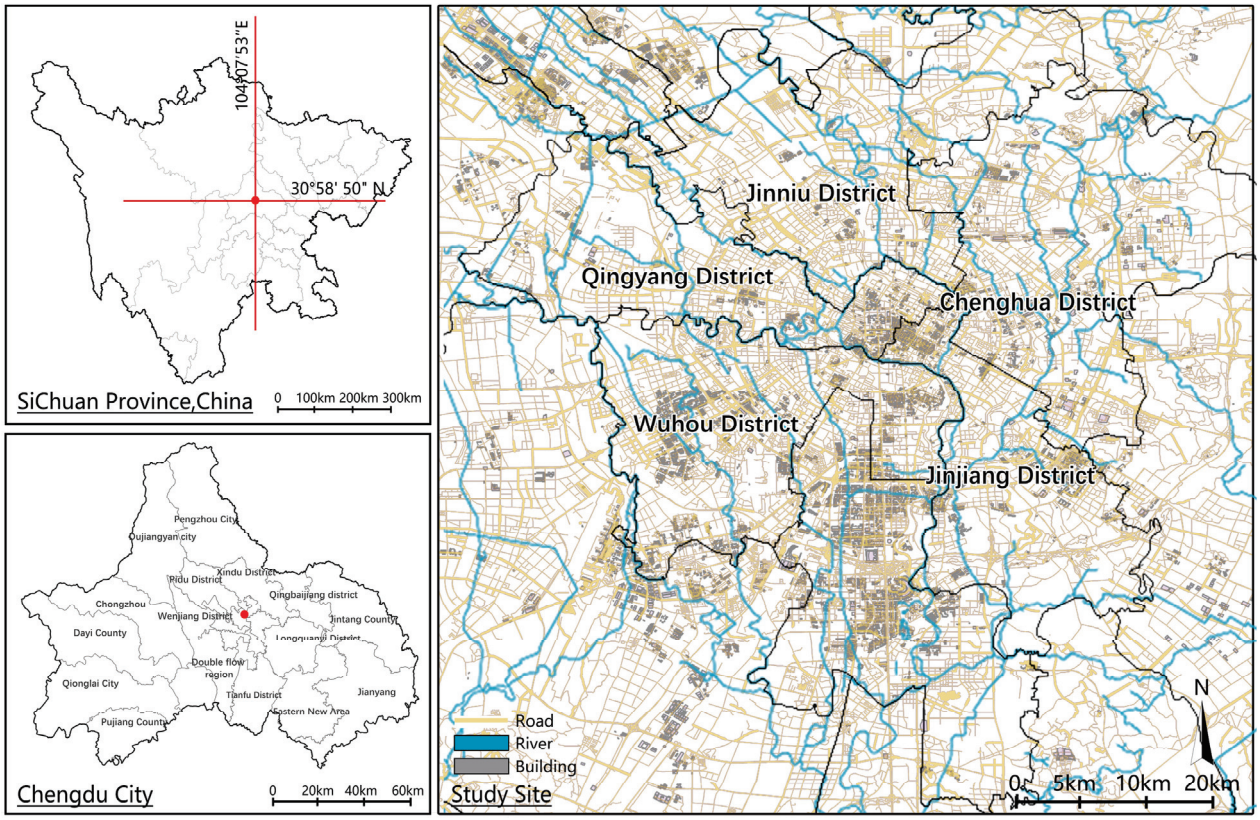



**Figure 1.** The location of the study area.

The online questionnaire consisted of three sections. The first section collected sociodemographic information from the residents, including their gender, age, level of education, and occupation. The second section categorized urban streets into three settings (community streets, waterfront paths, and urban greenways), and respondents were asked to choose a certain street setting as their daily walking environment. In the third section, we presented 46 factors compiled from the previous literature (Table 1) that may influence residents' choice of streets for walking, considering the knowledge of urban planning and landscape architecture. Residents were asked to indicate how each item influenced their choice of walking in a particular street setting on a scale from −3 to +3. Specifically, based on the street settings selected in the second section, −3 indicated a strong negative impact, where the street would not be chosen as a walking path due to the presence of the item, and +3 indicated a strong positive impact, where the street would definitely be chosen as a walking path due to the presence of the item. Figure 2 depicts the basic structure of the questionnaire. Please see Appendix A for the complete questionnaire.

**Table 1.** The list of all the independent variable factors for this study and the rationale for their selection.

| Environmental Factors | Environmental Factor Layer 1 | Environmental Factor Layer 2 | Rationale |
|---|---|---|---|
| Physical Environmental Factors | Infrastructure (road functional facilities) | Lighting<br>Guardrails<br>Signage<br>Garbage cans<br>Power poles<br>Billboards<br>Street cameras<br>High-voltage boxes | Streetscape elements such as guardrails, trash cans, and other streetscape elements are related to pedestrian walking preferences [52]; urban furniture is related to elements of the built environment and the pedestrian walking experience [53]. |

**Table 1.** *Cont.*

| Environmental Factors | Environmental Factor Layer 1 | Environmental Factor Layer 2 | Rationale |
|---|---|---|---|
| Physical Environmental Factors | Infrastructure (service facilities) | Retail stores<br>Restaurants<br>Teahouses<br>Bars<br>Cafes<br>Internet cafes<br>Hypermarkets<br>Mobile stalls<br>Toilets<br>Community clinics<br>Community fitness equipment<br>Community service centers | Changes in a built environment's general functions are significant, and pedestrians prefer routes that pass through more stores and services on the ground floor [31,54]. Providing public amenities can boost walkability [24–26]. When determining pedestrian route selection, public amenity data frequently include parks, restaurants, cafes, stores, medical services, and recreational facilities [27].<br>Some pedestrians' walking preferences are positively correlated with the presence of restrooms [55]. |
| | Infrastructure (road traffic facilities) | Bus Stations<br>Subway Stations<br>Cab stops<br>Bicycle parking | The volume of motor vehicle traffic also influences pedestrian preferences [56]. The presence of subway station entrances and exits enhances the vitality of a street. Additionally, bus stops, transit stations, and taxi stand influence residents' walking patterns [45,57]. |
| | Pedestrian conditions | Traffic lights<br>Crossroads<br>Ramps<br>Sidewalks<br>Pedestrian bridges<br>Underpasses<br>Level ground<br>Ground paving<br>Road greening<br>Green space along The street<br>Artificial landscape<br>Litter on the street<br>Seating<br>Gazebo<br>Fountain<br>Street tree box with seating | High activity levels near underpass entrances and pedestrian bridges also influence residents' walking activity [57]; pedestrian path preferences are associated with sidewalks [53]. Green space behavior is positively correlated with pedestrian walkability [53]; pedestrian walking and pocket parks are positively correlated [55]; benches are also associated with pedestrian walking [52,53]. |
| Aesthetic environmental factors | Environmental quality | Diversity<br>Facility Accessibility Uniformity<br>Novelty<br>Maintainability<br>Charm Sense of mystery | Diversity can be used to evaluate the impact of the environment on its inhabitants [58,59]; coherence has many characteristics, including a reflection of unity, balance, harmony, direction, and legibility, as well as understanding the totality of place and its relationship to itself [59–61]; mystery is associated with perceived complexity and attractiveness [58]. |
| | Subjective perception | Pleasant sounds<br>Pleasant odors | The multisensory nature of aesthetic experience is connected with the sounds of the built environment that impact pedestrians [58,62,63], the richness and diversity of odor characteristics, etc., which reflect the observed diversity of things [58,59,64]. |

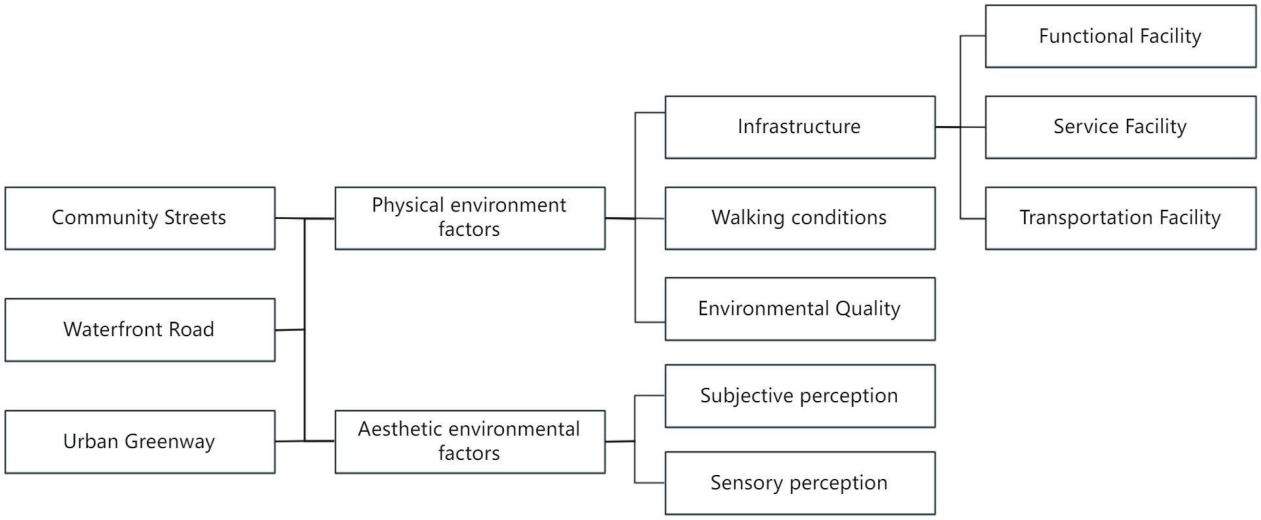



**Figure 2.** The basic framework of the online questionnaire.

### *2.3. Data Collection and Participants*

Using the Wenjuanxing platform (https://www.wjx.cn/, accessed on 30 March 2023), a web-based questionnaire was distributed to residents in the Chengdu metropolitan area. In addition, the authors posted a link to the questionnaire on their social media accounts and encouraged their friends and family to complete it. Data were collected from 25 September to 20 October 2022 from people who had resided in downtown Chengdu for more than three years. The questionnaire could be completed at any time throughout the day (including weekdays and weekends) by logging in. To ensure that the questionnaires were from the study area, only data from Chengdu were selected. Questionnaires with response times of less than one minute and incomplete questionnaires were excluded. Finally, 411 valid questionnaires were collected from a wide range of age groups and professions, with the participants taking an average of 9 min to complete the questionnaire.

### *2.4. Data Analysis*

Before distributing the questionnaires, a minimum number of required responses was determined using an online sample-size calculator (https://www.surveysystem.com/sscalc.html, accessed on 30 March 2023). Substituting the Chengdu metropolitan area's population of 9.52 million, we established a 95% confidence level and a 5% margin of error for the calculation, and the results indicated that a minimum sample size of 384 was required, so the current number of questionnaires was sufficient.

The final statistical analysis utilized 411 questionnaire responses, and Microsoft Excel was used to manage experimental data. The response frequencies and percentages for each population group were compiled and presented separately. The frequencies of residents' preferred walking street settings (community streets, waterfront paths, and urban greenways) were tallied separately. Multinomial logistic regression analysis was used to explore how respondents' sociodemographic characteristics influenced the choice of their preferred street setting. Moreover, reliability and validity tests of the questionnaire were conducted, as indicated by Cronbach's $\alpha$ coefficient and the Kaiser–Meyer–Olkin statistic, respectively. Subsequently, the means of the environmental factors (both physical and aesthetic) were calculated for each of the three walking street settings separately. Meanwhile, the Kruskal–Wallis H test (with post hoc comparisons) was used to analyze whether there was a difference in the response of 49 environmental factors between the three street settings. Subsequently, given that the scale ranged from $-3$ to +3, we labeled each factor according to one of the three levels of impact and based on the absolute value of the mean: almost no impact ($|\text{Mean}| < 1$), moderate impact ($2 > |\text{Mean}| > 1$), and strong impact ($|\text{Mean}| > 2$). No impact indicated that the public had no uniform tendency or

perceived little impact from this factor; therefore, it was not a design priority and could be ignored. A moderate impact meant that residents believed that the factor had a medium impact; therefore, these factors should not be disregarded. A strong impact indicated that most respondents concurred that the factor had a significant impact; consequently, these factors should be prioritized in the design. Finally, based on the findings, three design recommendations could be made for street environments. All statistical analyses were performed using Statistical Package for the Social Sciences (SPSS; version 20.0; SPSS Inc., Chicago, IL, USA), and the level of significance was set at $p < 0.05$.

## 3. Results

### 3.1. Basic Information

In total, 411 residents were included in this study. Table 2 displays the profiles of the respondents who participated with regard to gender, age, education level, occupation, driver's license status, and monthly income. According to the results, the percentage of female respondents was slightly higher than that of male respondents (58.64% to 41.36%). In addition, the number of respondents was similar in all three age groups (18–25, 26–55, and over 55 years old). The majority (40.63%, $N = 167$) had a bachelor's degree. The rest were classified as unemployed/retired (24.82%, $N = 102$), students (22.14%, $N = 91$), or corporate employees (16.55%, $N = 68$), which comprised the largest proportion of respondents. In addition, the majority had a driver's license (71.53%, $N = 294$) and earned between 4500 RMB and 8000 RMB (32.36%, $N = 133$). Moreover, Figure 3 shows the frequencies of residents' preferred walking street settings separately: community streets, $N = 57$; waterfront paths, $N = 152$; and urban greenways, $N = 202$.

**Table 2.** Profile of the respondents.

| Category | Sub-Category | Frequency ($N = 411$) | Percentage of Respondents (%) |
|---|---|---|---|
| Gender | Female | 241 | 58.64 |
| | Male | 170 | 41.36 |
| Age | 18–25 years old | 107 | 26.03 |
| | 26–55 years old | 145 | 35.28 |
| | 55+ years old | 159 | 38.69 |
| Educational Level | High School and below | 86 | 20.92 |
| | College | 86 | 20.92 |
| | Undergraduate | 167 | 40.63 |
| | Graduate | 72 | 17.52 |
| Occupation | Medical personnel (doctors, nurses) | 14 | 3.41 |
| | Teachers, lawyers, service industry workers (caterers/drivers/salesmen, etc.) | 35 | 8.52 |
| | Freelancer (e.g., writer/artist/photographer/guide, etc.) | 34 | 8.27 |
| | Workers (e.g., factory workers/construction workers/city sanitation workers, etc.) | 16 | 3.89 |
| | Company employees | 68 | 16.55 |
| | Career/civil servants/government workers | 32 | 7.79 |
| | Students | 91 | 22.14 |
| | Housewife | 19 | 4.62 |
| | No job/retired | 102 | 24.82 |
| Have a driver's license | Yes | 294 | 71.53 |
| | No | 117 | 28.47 |
| Monthly income | Less than 1500 RMB | 57 | 13.87 |
| | 1500–3500 RMB | 82 | 19.95 |
| | 3500–4500 RMB | 67 | 16.3 |
| | 4500–8000 RMB | 133 | 32.36 |
| | 8000–15,000 RMB | 55 | 13.38 |
| | More than 15,000 RMB | 17 | 4.14 |

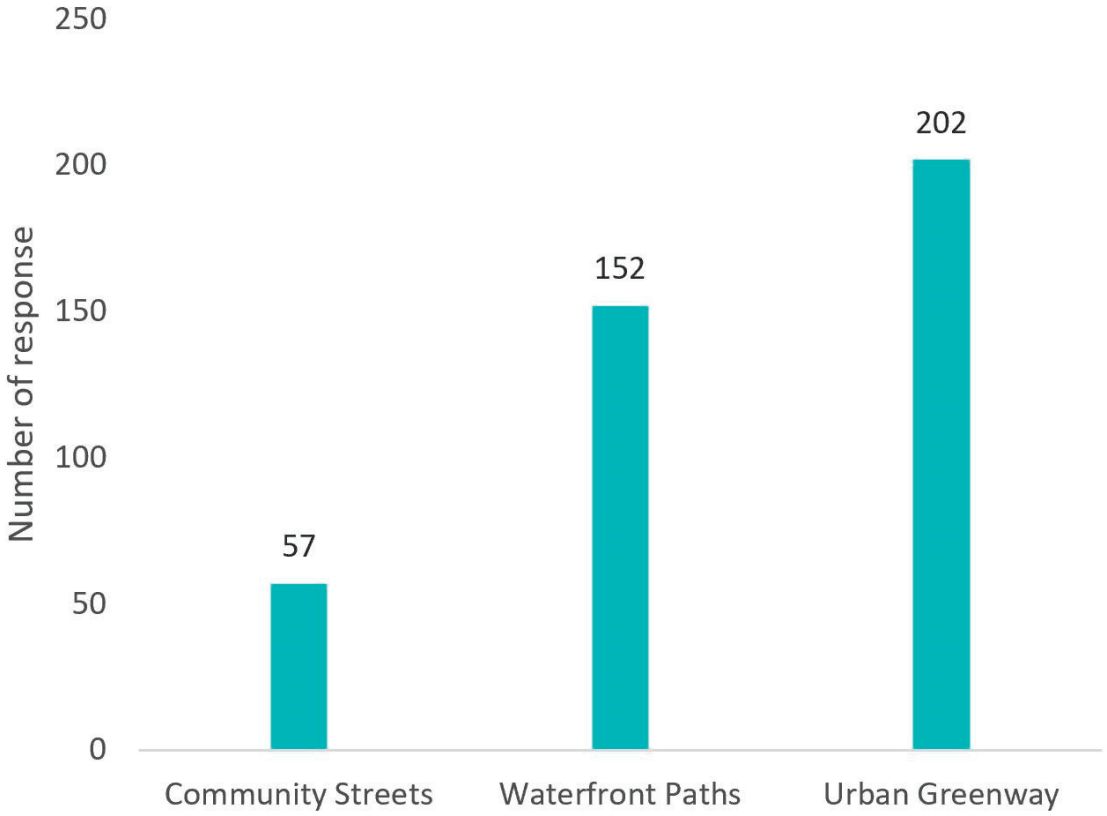



**Figure 3.** Statistical results of responses to three different street settings.

A multinomial logistic regression (with community streets as the reference group) was performed to explore how the respondents' sociodemographic characteristics influenced the choice of their preferred street setting. According to the results shown in Table 3, the model had a good degree of fit ($\chi^2$ = 22.777, $p$ = 0.012). Residents' preferences for street settings were independent of their sociodemographic variables, except for educational level. Respondents with higher educational levels were more likely to prefer waterfront paths than community streets (Exp (B) = 1.715, 95% C. I. 1.141–2.577, $p$ = 0.009).

**Table 3.** Results of multinomial logistic regression of sociodemographic characteristics in three street settings (Community Street as the reference category).

| Street Settings (Ref. Category: Community Streets) | | B | Standard Error | Wald | df | Sig. | Exp (B) | Confidence Interval 95% of Exp (B) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Lower Limit | Upper Limit |
| Waterfront Paths | intercept | 0.691 | 1.273 | 0.295 | 1 | 0.587 | - | | |
| | Age | −0.203 | 0.178 | 1.306 | 1 | 0.253 | 0.816 | 0.576 | 1.156 |
| | Gender | −0.125 | 0.349 | 0.128 | 1 | 0.720 | 0.883 | 0.446 | 1.748 |
| | Education | 0.539 | 0.208 | 6.741 | 1 | 0.009 * | 1.715 | 1.141 | 2.577 |
| | Car Access | 0.365 | 0.410 | 0.793 | 1 | 0.373 | 1.441 | 0.645 | 3.219 |
| | Income | −0.161 | 0.158 | 1.035 | 1 | 0.309 | 0.851 | 0.624 | 1.161 |
| Urban Greenways | intercept | 2.353 | 1.207 | 3.802 | 1 | 0.051 | - | | |
| | Age | −0.263 | 0.170 | 2.397 | 1 | 0.122 | 0.769 | 0.551 | 1.073 |
| | Gender | −0.164 | 0.332 | 0.243 | 1 | 0.622 | 0.849 | 0.443 | 1.628 |
| | Education | 0.160 | 0.197 | 0.660 | 1 | 0.417 | 1.174 | 0.797 | 1.728 |
| | Car Access | 0.141 | 0.391 | 0.130 | 1 | 0.718 | 1.152 | 0.535 | 2.479 |
| | Income | −0.104 | 0.152 | 0.468 | 1 | 0.494 | 0.901 | 0.669 | 1.214 |
| AIC = 465.437 | | | | | | | | | |
| BIC = 513.660 | | | | | | | | | |
| Likelihood ratio: $\chi^2$ = 22.777, df = 10, $p$ = 0.012 | | | | | | | | | |

Note: * $p$ < 0.01. df, degree of freedom. AIC, Akaike information criterion; BIC, Bayesian information criterion.

### *3.2. Physical Environmental Factors Affecting the Choice of Streets for Walking*

Table 4 shows an overall assessment of the physical environmental factors. First, the questionnaire was analyzed for reliability, and the results indicated that the five physical environment dimensions were set reliably as all Cronbach's α coefficients exceeded 0.5 [65], ranging from 0.666 to 0.866. According to Landis and Koch (1977), a Cronbach's alpha value greater than 0.8 indicates good internal consistency [66]. Therefore, the transportation facility dimension (Cronbach's alpha = 0.866) and walking conditions dimension (Cronbach's alpha = 0.802) both demonstrated good reliability. A validity test was then conducted, and the results indicated that the current setting of the physical environment dimension was reasonable, and the Kaiser–Meyer–Olkin statistic score was 0.879 ($p < 0.001$).

**Table 4.** Overall assessment of physical environmental factors.

| Dimensions | Items | Differential Analysis on Three Streets | | | Reliability Analysis | Validity Analysis | |
|---|---|---|---|---|---|---|---|
| | | Statistics | df | Sig. | Cronbach's Alpha | Kaiser-Meyer-Olkin Statistics | Sig. |
| Functional Facility | Lighting | 1.383 | 2 | 0.501 | 0.666 | 0.879 | <0.001 |
| | Guardrails | 0.802 | 2 | 0.670 | | | |
| | Signage | 3.057 | 2 | 0.217 | | | |
| | Garbage cans | 1.283 | 2 | 0.527 | | | |
| | Wire poles | 4.987 | 2 | 0.083 | | | |
| | Billboards | 1.126 | 2 | 0.569 | | | |
| | Street cameras | 2.684 | 2 | 0.261 | | | |
| | High voltage boxes | 2.122 | 2 | 0.346 | | | |
| Service Facility | Retail stores | 0.552 | 2 | 0.759 | 0.774 | | |
| | Restaurants | 1.332 | 2 | 0.514 | | | |
| | Teahouses | 3.941 | 2 | 0.139 | | | |
| | Bars | 0.296 | 2 | 0.862 | | | |
| | Cafes | 4.558 | 2 | 0.102 | | | |
| | Internet cafes | 0.613 | 2 | 0.736 | | | |
| | Hypermarkets | 4.972 | 2 | 0.083 | | | |
| | Mobile stalls | 2.424 | 2 | 0.298 | | | |
| | Toilets | 0.130 | 2 | 0.937 | | | |
| | Community clinics | 1.577 | 2 | 0.455 | | | |
| | Community fitness equipment | 2.025 | 2 | 0.363 | | | |
| | Community service centers | 2.482 | 2 | 0.289 | | | |
| Transportation Facility | Bus Stations | 4.987 | 2 | 0.083 | 0.866 | | |
| | Subway Stations | 3.196 | 2 | 0.202 | | | |
| | Cab stands | 2.135 | 2 | 0.344 | | | |
| | Bicycle parking | 0.262 | 2 | 0.877 | | | |
| Walking Conditions | Traffic signals | 0.224 | 2 | 0.894 | 0.802 | | |
| | Crossroads | 4.355 | 2 | 0.113 | | | |
| | Ramps | 0.180 | 2 | 0.914 | | | |
| | Sidewalks | 0.443 | 2 | 0.801 | | | |
| | Pedestrian bridges | 1.782 | 2 | 0.410 | | | |
| | Underpasses | 0.753 | 2 | 0.686 | | | |
| | Leveled ground | 4.604 | 2 | 0.100 | | | |
| | Paved Ground | 3.312 | 2 | 0.191 | | | |
| Environmental Quality | Road greenery | 3.248 | 2 | 0.197 | 0.724 | | |
| | Green space along the street | 5.438 | 2 | 0.066 | | | |
| | Artificial landscape | 2.992 | 2 | 0.224 | | | |
| | Litter on the street | 0.259 | 2 | 0.879 | | | |
| | Seating | 0.242 | 2 | 0.886 | | | |
| | Gazebo | 4.987 | 2 | 0.083 | | | |
| | Fountain | 1.990 | 2 | 0.370 | | | |
| | Street tree box with seating | 1.275 | 2 | 0.529 | | | |

Finally, to examine whether the response of residents to physical environmental factors was significantly different between the three street settings, the Kruskal–Wallis H test (with a post hoc test) was executed. Based on the results of the Kruskal–Wallis H test, no significant differences ($p > 0.05$) in response were observed for any of the 40 items from the five physical environment factors, indicating similar response trends among the respondents in three street settings. As there was no significant difference, the impact levels of each item were marked in the follow-up results according to the absolute value of the mean: almost no impact ($|\text{mean}| < 1$), moderate impact ($2 > |\text{mean}| > 1$), and strong impact ($|\text{mean}| > 2$).

3.2.1. Infrastructure

The infrastructure dimension was separated into three sub-dimensions: functional street facilities, service facilities, and transportation facilities (Table 5).

**Table 5.** Residents' responses to infrastructure items for the three street settings.

| Dimensions | Items | Community Streets (*N* = 57) | | | | Waterfront Paths (*N* = 152) | | | | Urban Greenways (*N* = 202) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **M** | **N** | ○ | △ | **M** | **N** | ○ | △ | **M** | **N** | ○ | △ |
| Functional Street Facility | Lighting | 1.79 | | √ | | 1.82 | | √ | | 1.90 | | √ | |
| | Guardrails | 1.32 | | √ | | 1.07 | | √ | | 1.16 | | √ | |
| | Signage | 1.75 | | √ | | 1.40 | | √ | | 1.45 | | √ | |
| | Garbage cans | 0.11 | √ | | | 0.32 | √ | | | 0.15 | √ | | |
| | Wire poles | −1.23 | | √ | | −0.64 | √ | | | −0.78 | √ | | |
| | Billboards | −0.70 | √ | | | −0.59 | √ | | | −0.53 | √ | | |
| | Street cameras | 0.93 | √ | | | 1.18 | | √ | | 1.00 | | √ | |
| | High voltage boxes | −1.12 | | √ | | −1.06 | | √ | | −1.28 | | √ | |
| Service Facility | Retail stores | 1.35 | | √ | | 1.21 | | √ | | 1.24 | | √ | |
| | Restaurants | 1.04 | | √ | | 0.85 | √ | | | 0.76 | √ | | |
| | Teahouses | 0.02 | √ | | | 0.50 | √ | | | 0.35 | √ | | |
| | Bars | 0.04 | √ | | | −0.08 | √ | | | −0.11 | √ | | |
| | Cafes | −0.23 | √ | | | 0.24 | √ | | | 0.15 | √ | | |
| | Internet cafes | −0.65 | √ | | | −0.42 | √ | | | −0.50 | √ | | |
| | Hypermarkets | 1.42 | | √ | | 0.97 | √ | | | 0.96 | √ | | |
| | Mobile stalls | 0.89 | √ | | | 0.71 | √ | | | 0.45 | √ | | |
| | Toilets | 1.35 | | √ | | 1.20 | | √ | | 1.17 | | √ | |
| | Community clinics | 1.07 | | √ | | 0.76 | √ | | | 0.87 | √ | | |
| | Community fitness equipment | 1.93 | | √ | | 1.74 | | √ | | 1.74 | | √ | |
| | Community service centers | 1.07 | | √ | | 0.96 | √ | | | 1.20 | | √ | |
| Transportation Facility | Bus Stations | 1.33 | | √ | | 0.89 | √ | | | 1.32 | | √ | |
| | Subway Stations | 0.96 | √ | | | 0.80 | √ | | | 1.12 | | √ | |
| | Cab stands | 0.81 | √ | | | 0.59 | √ | | | 0.83 | √ | | |
| | Bicycle parking | 0.96 | √ | | | 0.95 | √ | | | 1.01 | | √ | |

M = Mean value, N = almost no impact, ○ = moderate impact, △ = strong impact.

First, for the functional street facility, the impact of lighting, guardrails, signage, billboards, and high voltage boxes showed similar trends for all three street settings. Specifically, lighting (1.79, 1.82, 1.90), guardrails (1.32, 1.07, 1.16), signage (1.75, 1.4, 1.45), and high-voltage boxes (−1.12, −1.06, −1.28) had a moderate impact on the choice of the street for walking, whereas billboards had a negative but small impact (−0.70, −0.59, −0.53). Notably, wire poles and street cameras had different effects on the three street setting options. Wire poles had a moderately negative impact on community streets (−1.23), whereas this negative impact was negligible for residents who chose waterfront paths (−0.64) and urban greenways (−0.78). Street cameras had almost no impact on the selection of community streets (0.93) but had a moderately positive impact on the selection of the other two street settings (1.18, 1.00).

The impact of retail stores, teahouses, bars, cafes, internet cafes, toilets, and community fitness equipment, on the selection of the three street settings was identical. Specifically, retail stores (1.35, 1.21, 1.24), toilets (1.35, 1.20, 1.17), and community fitness equipment (1.93, 1.74, 1.74) had moderate impacts in all three environments. However, restaurants, hypermarkets, mobile stalls, community clinics, and community service centers had different effects on the selection of the three street settings. For community streets, restaurants (1.04), hypermarkets (1.42), and community clinics (1.07) had moderately positive effects, whereas, for the other two street settings, these service facilities had almost no effect.

Regarding transportation facilities, the cab stands had almost no impact on residents' preferences for the three street settings (0.81, 0.59, 0.83). For community streets and urban greenways, bus stations (1.33, 1.32) had a moderately positive impact, whereas they had almost no impact (0.89) on waterfront paths. Subway stations (1.12) and bicycle parking (1.00) had a moderately positive impact only on urban greenways.

#### 3.2.2. Walking Conditions

Table 6 displays the outcomes of the walking condition dimensions. Crossroads, ramps, pedestrian bridges, and underpasses had almost no impact on the selection of these three street settings. In addition, in all three street settings, traffic signals (1.23, 1.1, 1.12), sidewalks (1.25, 1.35, 1.29), and leveled ground (1.98, 1.76, 1.99) had moderately positive impacts. It was also observed that the paved ground dimension had a moderately positive impact on waterfront paths (1.69) and urban greenways (1.66), compared to a strong impact on community streets (2.02).

**Table 6.** Residents' responses to walking condition items for the three street settings.

| Pedestrian Conditions | Community Streets (*N* = 57) | | | | Waterfront Paths (*N* = 152) | | | | Urban Greenways (*N* = 202) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **M** | **N** | ○ | △ | **M** | **N** | ○ | △ | **M** | **N** | ○ | △ |
| Traffic signals | 1.23 | | √ | | 1.1 | | √ | | 1.12 | | √ | |
| Crossroads | 0.96 | √ | | | 0.63 | √ | | | 0.49 | √ | | |
| Ramps | 0.39 | √ | | | 0.33 | √ | | | 0.41 | √ | | |
| Sidewalks | 1.25 | | √ | | 1.35 | | √ | | 1.29 | | √ | |
| Pedestrian bridges | 0.63 | √ | | | 0.67 | √ | | | 0.90 | √ | | |
| Underpasses | 0.63 | √ | | | 0.49 | √ | | | 0.47 | √ | | |
| Leveled ground | 1.98 | | √ | | 1.76 | | √ | | 1.99 | | √ | |
| Paved ground | 2.02 | | | √ | 1.69 | | √ | | 1.66 | | √ | |

M = Mean value, N = almost no impact, ○ = moderate impact, △ = strong impact.

#### 3.2.3. Environmental Quality

Table 7 shows the results for the environmental quality dimension. There was a moderately positive impact of gazebos (1.63, 1.71, 1.97), fountains (1.88, 1.64, 1.65), and street tree boxes with seating (1.82, 1.82, 1.95) on the choice of all three street settings. For both community streets and urban greenways, seating (2.04, 2.02) had a strong positive impact, indicating that the presence of seating was crucial to residents in determining the choice to walk on these two types of streets. In addition, for waterfront paths and urban greenways, road greenery (2.20, 2.21), green space along the street (2.22, 2.13), and artificial landscapes (2.06, 2.00) had a strong positive impact, indicating that residents strongly preferred both paths because of the presence of green and artificial elements. Not surprisingly, litter had a non-negligible negative impact on any type of street choice (−1.7, −1.72, −1.59).

### *3.3. Aesthetic Environmental Factors Affecting the Choice of Streets for Walking*

Table 8 shows the overall assessment of aesthetic environmental factors. The questionnaire reliability analysis results indicated that the two aesthetic environment dimensions (Subjective Perception and Sensory Perception) were set reliably, as all Cronbach's α coefficients ranged from 0.573 to 0.831. The validity test indicated that the current setting of the aesthetic environment dimension was reasonable, and the Kaiser–Meyer–Olkin statistic

was 0.882 ($p < 0.001$). Similar to the physical environmental factors and, based on the results of the Kruskal–Wallis H test, no significant differences ($p > 0.05$) in responses were observed for any of the nine items from the two aesthetic environmental factors, indicating similar response trends among the respondents in the three street settings. As there was no significant difference, the impact levels of each item were marked in the follow-up results according to the absolute value of the mean: almost no impact (|mean| < 1), moderate impact (2 > |mean| > 1), and strong impact (|mean| > 2).

**Table 7.** Residents' responses to environmental quality items for the three street settings.

| Pedestrian Conditions | Community Streets (*N* = 57) | | | | Waterfront Paths (*N* = 152) | | | | Urban Greenways (*N* = 202) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **M** | **N** | ○ | △ | **M** | **N** | ○ | △ | **M** | **N** | ○ | △ |
| Road greenery | 1.98 | | √ | | 2.20 | | | √ | 2.21 | | | √ |
| Green space along the street | 1.88 | | √ | | 2.22 | | | √ | 2.13 | | | √ |
| Artificial landscape | 1.77 | | √ | | 2.06 | | | √ | 2.00 | | | √ |
| Litter on the street | −1.7 | | √ | | −1.72 | | √ | | −1.59 | | √ | |
| Seating | 2.04 | | | √ | 1.93 | | √ | | 2.02 | | | √ |
| Gazebo | 1.63 | | √ | | 1.71 | | √ | | 1.97 | | √ | |
| Fountain | 1.88 | | √ | | 1.64 | | √ | | 1.65 | | √ | |
| Street tree box with seating | 1.82 | | √ | | 1.82 | | √ | | 1.95 | | √ | |

M = Mean value, N = almost no impact, ○ = moderate impact, △ = strong impact.

**Table 8.** Overall assessment of aesthetic environmental factors.

| Dimensions | Items | Differential Analysis on Three Streets | | | Reliability Analysis | Validity Analysis | |
|---|---|---|---|---|---|---|---|
| | | **Statistics** | **df** | **Sig.** | **Cronbach's Alpha** | **Kaiser-Meyer-Olkin Statistics** | **Sig.** |
| Subjective Perception | Diversity | 0.499 | 2 | 0.779 | 0.831 | 0.882 | <0.001 |
| | Facility Accessibility | 0.034 | 2 | 0.983 | | | |
| | Uniformity | 4.213 | 2 | 0.122 | | | |
| | Novelty | 0.368 | 2 | 0.832 | | | |
| | Maintainability | 3.498 | 2 | 0.174 | | | |
| | Charm | 2.512 | 2 | 0.285 | | | |
| | Sense of mystery | 3.000 | 2 | 0.223 | | | |
| Sensory Perception | Pleasant sounds | 1.895 | 2 | 0.388 | 0.573 | | |
| | Pleasant odors | 0.634 | 2 | 0.728 | | | |

The results of the impact of aesthetic quality are listed in Table 9. The diversity (1.65, 1.63, 1.71), facility accessibility (1.79, 1.80, 1.83), uniformity (1.63, 1.46, 1.72), novelty (1.65, 1.61, 1.69), and sense of mystery (1.77, 1.67, 1.52) dimensions had positive moderate impacts on the three street setting choices. Notably, the maintainability dimension (2.10) had a strong positive impact on the choice of urban greenways. For community streets and urban greenways, charm dimensions (2.02, 2.00) had a strong positive impact, whereas they had a moderate positive impact on waterfront paths (1.87). In addition, pleasant odors (2.01) had a strong positive impact on waterfront paths but a moderate impact on the other two settings (1.86, 1.97). The pleasant sounds dimension (1.13, 1.41, 1.25) also had a moderate positive impact on all three streets.

**Table 9.** Residents' responses to aesthetic environmental quality items for the three street settings.

| Dimensions | Items | Community Streets (*N* = 57) | | | | Waterfront Paths (*N* = 152) | | | | Urban Greenways (*N* = 202) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **M** | **N** | ○ | △ | **M** | **N** | ○ | △ | **M** | **N** | ○ | △ |
| Subjective perception | Diversity | 1.65 | | √ | | 1.63 | | √ | | 1.71 | | √ | |
| | Facility Accessibility | 1.79 | | √ | | 1.8 | | √ | | 1.83 | | √ | |
| | Uniformity | 1.63 | | √ | | 1.46 | | √ | | 1.72 | | √ | |
| | Novelty | 1.65 | | √ | | 1.61 | | √ | | 1.69 | | √ | |
| | Maintainability | 1.89 | | √ | | 1.94 | | √ | | 2.10 | | | √ |
| | Charm | 2.02 | | | √ | 1.87 | | √ | | 2.00 | | | √ |
| | Sense of mystery | 1.77 | | √ | | 1.67 | | √ | | 1.52 | | √ | |
| Sensory perception | Pleasant sounds | 1.13 | | √ | | 1.41 | | √ | | 1.25 | | √ | |
| | Pleasant odors | 1.86 | | √ | | 2.01 | | | √ | 1.97 | | √ | |

M = Mean value, N = almost no impact, ○ = moderate impact, △ = strong impact.

## 4. Discussion

### *4.1. Sociodemographic Characteristic's Impact on Residents' Preference to Walking Street*

The frequencies of residents' preferred walking street settings (community streets, waterfront paths, and urban greenways) were tallied separately, and a multinomial logistic regression analysis was used to explore how respondents' sociodemographic characteristics influenced the choice of their preferred street setting. The above test revealed that residents' preference for street settings were independent of sociodemographic variables, except for their educational level. Specifically, respondents with higher educational levels were more likely to prefer streets with water elements (or blue spaces) than community streets (pure built environment). This is a valuable finding; to the best of our knowledge, few studies have addressed the association between street environment preferences and demographic characteristics. Thus, our findings answer the first question posed in this study and have implications for the development of future outdoor exercise interventions in cities.

### *4.2. Impact of Physical Environmental Dimensions on the Three Street Settings*

According to the results, we determined that the physical environmental dimensions (infrastructure, walking conditions, and environmental quality) had an impact on residents' choices and that these impacts exhibited differences across street settings.

Community streets, restaurants, hypermarkets, community clinics, and community service centers had a greater impact, and paved streets had a stronger impact. A residential street with favorable physical environmental factors encouraged residents to walk [67,68]. Thus, it is likely that residents who prefer to walk on community streets are more concerned with the infrastructure on those streets. Consequently, infrastructure, especially functional street facilities, has a greater impact on their choice.

For the waterfront path, road greenery, green spaces along the street, and artificial landscapes had a greater impact. However, street infrastructure had a smaller impact. This was likely because residents who prefer to walk on waterfront paths are more concerned with the natural landscape, green space, and vegetation, which all impact the waterfront's natural environment [69]. In addition, residents who prefer waterfront paths are more concerned with natural environmental quality; consequently, environmental quality has a greater impact.

Road greenery, green spaces along the street, artificial landscapes, and seating had a strong impact on urban greenways. Moreover, the transportation facility dimensions in the infrastructure, such as bus stations, subway stations, and bicycle parking, had a greater impact on residents' walking on the greenway than the other two paths. This is likely because green spaces can provide health benefits and have a positive impact on residents [20,27]; consequently, residents subconsciously associate a higher degree of the green environment with positive benefits. Furthermore, urban greenways are often located far from residential areas (such as at the edge of cities), which results in higher

transportation facility needs. Thus, environmental quality and transportation facilities had a greater impact on residents who chose urban greenways.

### *4.3. Impact of Aesthetic Environmental Dimensions on the Three Street Settings*

Based on these findings, we determined that the aesthetic quality of the environment had a positive and moderate impact on the residents of all three environments and that the overall aesthetic quality of the environment had a greater impact on residents than their physical environment. Street maintenance had a stronger impact on residents who chose urban greenways in terms of the impact of the subjective perception of residents' street aesthetics. Improving or maintaining the quality of the built environment may increase residents' walking activities [67].

Hence, urban greenways should prioritize the maintenance of streets, including the maintenance of street infrastructure and green spaces. In addition, the charm has a stronger impact on community streets and urban green spaces; consequently, the design or renovation of community streets and urban greenways should prioritize attracting more residents based on contemporary everyday aesthetic concepts [70].

The sensory perception of a street can have an impact on residents' choice of all three paths, as they prefer to hear pleasant sounds from nature over city noise. Therefore, designs should consider residents' senses of sound and odor [71]. Notably, odors have a strong impact on residents who choose waterfront paths; therefore, plants that release pleasant odors should be used to design or renovate waterfront paths.

### *4.4. Study Significance and Implications*

According to this study, the physical and aesthetic qualities of the street environment can directly influence residents walking preferences. Consequently, through the design of the physical and aesthetic qualities of different types of street environments, it is possible to increase their use by residents. This can potentially increase their walking time and frequency and promote health. Based on the results of this survey, three environmental factors in different street settings had a non-negligible impact on residents' selection of preferred walking streets and are summarized in Table 10.

**Table 10.** Residents' responses for preferred walking environment items for the three street settings.

| Factors | Dimensions | Community Streets | | Waterfront Paths | | Urban Greenways | |
|---|---|---|---|---|---|---|---|
| | | **Moderate Impact** | **Strong Impact** | **Moderate impact** | **Strong Impact** | **Moderate Impact** | **Strong Impact** |
| Physical environmental factors | Infrastructure | Lighting<br>Guardrails<br>Signage<br>Wire poles<br>High-voltage boxes<br>Retail stores<br>Restaurants<br>Hypermarkets<br>Toilets<br>Community clinics<br>Community fitness equipment<br>Community service centers<br>Bus stations | | Lighting<br>Guardrails<br>Signage<br>Street cameras<br>High voltage boxes<br>Retail stores<br>Toilets<br>Community fitness equipment | | Lighting<br>Guardrails<br>Signage<br>Street cameras<br>High voltage boxes<br>Retail stores<br>Toilets<br>Community fitness equipment<br>Community service canters<br>Bus stations<br>Subway stations<br>Bicycle parking | |

**Table 10.** *Cont.*

| Factors | Dimensions | Community Streets | | Waterfront Paths | | Urban Greenways | |
|---|---|---|---|---|---|---|---|
| | | **Moderate Impact** | **Strong Impact** | **Moderate impact** | **Strong Impact** | **Moderate Impact** | **Strong Impact** |
| Aesthetic environmental factors | Pedestrian conditions | Traffic signals<br>Sidewalk<br>Leveled ground | Paved ground | Traffic signals<br>Sidewalk<br>Leveled ground<br>Paved ground | | Traffic signal<br>sidewalk<br>Leveled ground<br>Paved ground | |
| | Environmental quality | Road greening<br>Green spaces along the street<br>Artificial landscape<br>Litter on the street<br>Gazebo<br>Fountain<br>street tree box with seating | Seating | Litter on the street<br>Seating<br>Gazebo<br>Fountain<br>street tree box with seating | Road greening<br>Green spaces along the street<br>Artificial landscape | Litter on the street<br>Gazebo<br>Fountains<br>street tree box with seats | Road greening<br>Green spaces along the street<br>Artificial landscape<br>Seating |
| | Subjective perception | Diversity<br>Facility<br>Accessibility<br>Uniformity<br>Novelty<br>Maintainability<br>Sense of mystery | Charm | Diversity<br>Facility<br>Accessibility<br>Uniformity<br>Novelty<br>Maintainability<br>Charm<br>Sense of mystery | | Diversity<br>Facility<br>Accessibility<br>Uniformity<br>Novelty<br>Fascination<br>Sense of mystery | Maintainability<br>Charm |
| | Sensory perception | Pleasant sounds<br>Pleasant odors | | Pleasant sounds | Pleasant odors | Pleasant sounds<br>Pleasant odors | |

Based on this study, design solutions for the three distinct street environments were proposed. First, because residents are more concerned with the physical environment of community streets (Figure 4), infrastructure on community streets should be well-developed, including lighting, guardrails, seating, and paved ground. However, it has been discovered that high-voltage boxes and wire poles have a negative impact on residents, and street designers should conceal these facilities for the sake of aesthetics. In addition, the findings show that residents are also interested in restaurants, hypermarkets, and community clinics on community streets. Hence, these facilities are more likely to encourage residents to walk on community streets. Residents of community streets are also interested in restrooms and exercise equipment; therefore, there should be an abundance of street facilities for walking and resting.

Second, in the design of a waterfront path environment (Figure 5), factors such as street cameras, seating, gazebos, fountains, signage, and artificial landscapes should be incorporated. In addition, the natural environment plays a significant role in encouraging residents to walk, so physical environmental facilities should be integrated into the natural environment to create a natural recreational public space, as residents prefer the environment's natural state. When establishing street facilities, road greenery, green areas along the street, and plants that emit pleasant odors should be considered, and residents should be provided with sufficient space for walking and other activities.

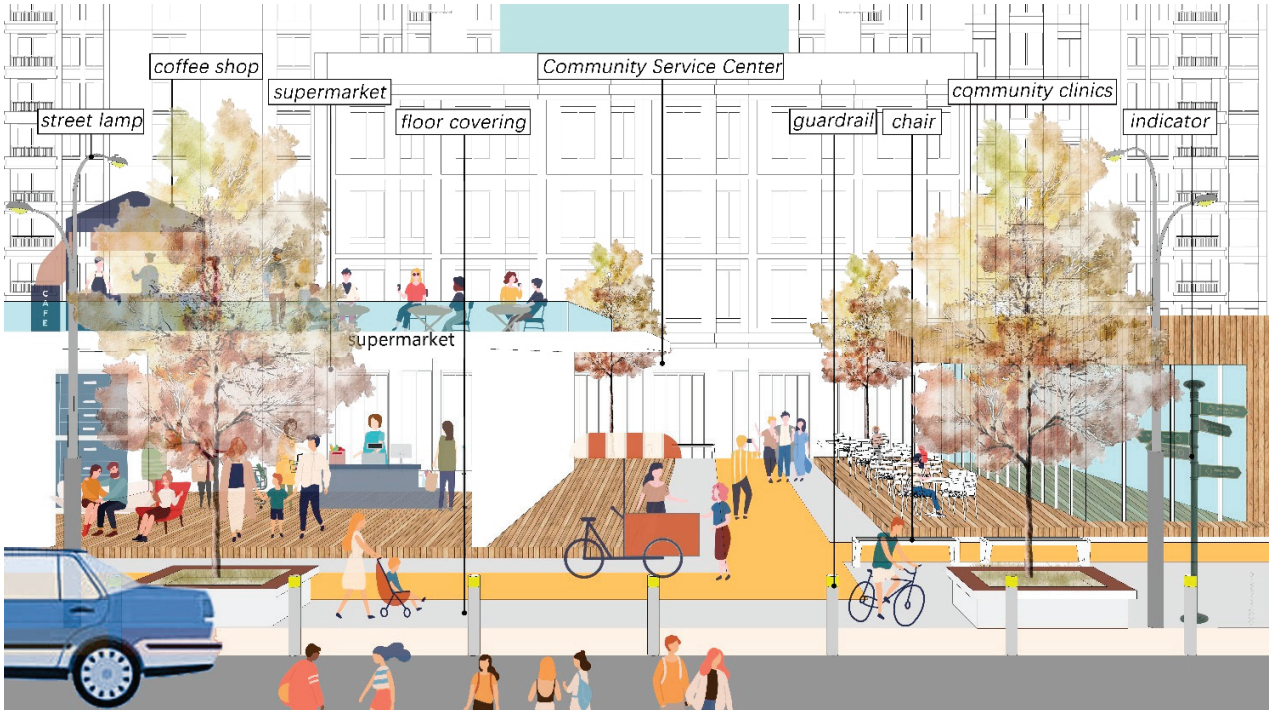



**Figure 4.** Community street design scenes.

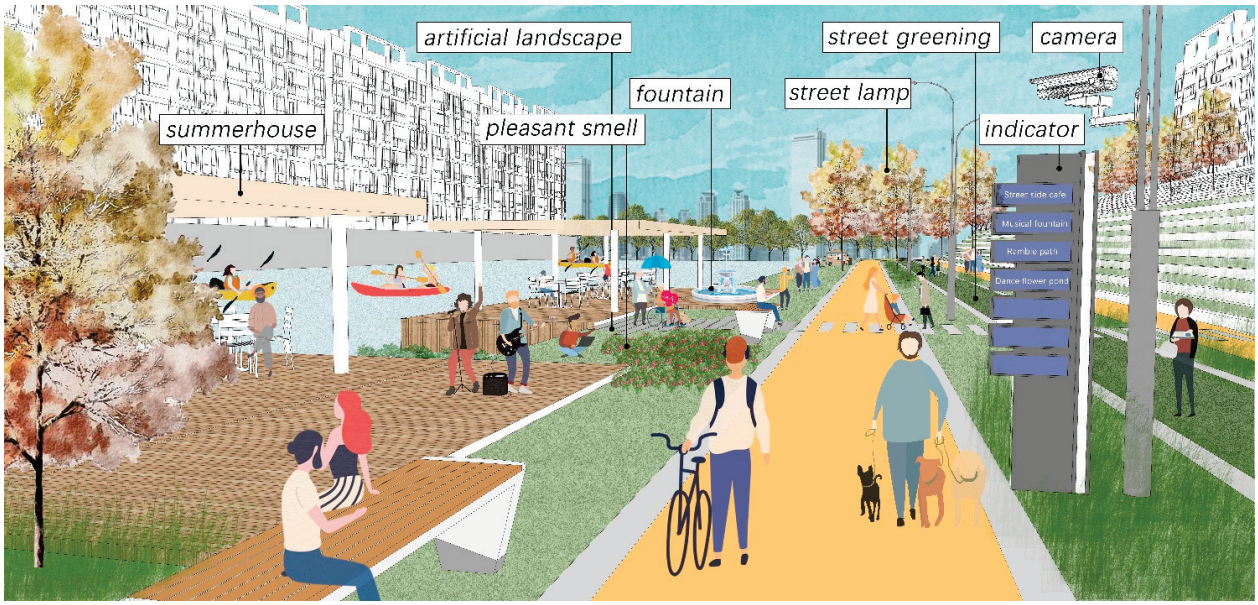



**Figure 5.** Waterfront path design scenes.

Third, infrastructure such as community service centers, subway stations, bicycle parking, seating, and artificial landscapes in an urban greenway environment (Figure 6) is worth considering. Additionally, the presence of road greenery and green spaces along the street is a significant factor that encourages residents to walk. Therefore, green spaces on urban greenways should satisfy the walking needs of residents, allowing them to experience the natural environment of urban greenways and provide pedestrians with green spaces for rest and recreation. Furthermore, streets should be well maintained to appeal to residents and encourage them to walk.

**Figure 6.** Urban greenway design scenes.

## 5. Conclusions

These three different types of street environments have different impacts on the walking behavior of residents. A well-designed or renovated street environment can boost the walking time and frequency of residents in different street environments. Therefore, a street environment is essential for establishing a healthy environment for residents. This study examined the impact of street environmental factors on residents in three street environments (community streets, waterfront paths, and urban greenways) using a questionnaire survey for 411 Chengdu metropolitan residents. Current research has found that: (1) people with higher levels of education prefer streets with water bodies as walking paths; (2) the environmental quality of physical and aesthetic aspects has an impact on residents' choices, and the aesthetic environment quality has a stronger impact; (3) the impact of most infrastructure items on community streets are stronger than on other streets; (4) residents are more concerned about the environmental quality of waterfront paths and urban greenways. In addition, the design inclinations of urban planners vary depending on the street environment. Community streets should emphasize street infrastructure and provide adequate walking conditions and environmental quality for pedestrians. Waterfront paths should emphasize streetscapes and pedestrian-friendly roads to ensure there is sufficient space for residents to relax and enjoy recreation. Urban greenways should offer sufficient green space for city residents to experience the city's greenery.

In summary, this study used a bottom-up approach to identify the varying impacts of environmental dimensions on residents walking in three distinct environmental streets and, in doing so, assists future policymakers and urban planners in implementing various street designs or renovations. Consequently, different types of urban streets can be designed or renovated based on these findings. They can be modified to incorporate different physical environmental factors, as well as aesthetic environmental factors, to attract residents and encourage more walking activities to improve physical and mental health.

**Author Contributions:** Conceptualization, Q.Y., S.L. and J.J.; methodology, Q.Y. and S.L.; software, Q.Y., S.L. and J.J.; validation, Q.Y. and S.L.; formal analysis, Q.Y. and S.L.; resources, Q.Y., S.L. and J.J.; data curation, Q.Y., S.L. and J.J.; writing—original draft preparation, Q.Y. and S.L.; writing—review and editing, Q.Y. and S.L.; visualization, Q.Y.; supervision, Q.Y., S.L. and J.J.; funding acquisition, Q.Y. All authors have read and agreed to the published version of the manuscript.

**Funding:** This project is supported by Jiangsu Funding Program for Excellent Postdoctoral Talent (2022ZB599) and the special fund of Collaborative Innovation Center of Soochow University and Suzhou Yuanke Ecological Construction Group (SY2022003).

**Data Availability Statement:** The data that support the findings of this study are available from the first author Q.Y. and corresponding author, S.L., upon reasonable request.

**Acknowledgments:** We would like to thank the reviewers and editors for their constructive comments that helped us improve the quality of the manuscript. We appreciate the valuable information provided by all the anonymous interviewees.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

Survey of the impact of street facilities and environment on pedestrians

1. Age [Single-choice]

( ) 18–25 years old
( ) 26–55 years old
( ) 55 years old or older

2. Gender [Single-choice]

( ) Male
( ) Female

3. Occupation [Single-choice]

( ) Medical personnel (doctors, nurses)
( ) Teachers, lawyers, service industry workers (caterers/drivers/salesmen, etc.)
( ) Freelancer (e.g., writer/artist/photographer/guide, etc.)
( ) Workers (e.g., factory workers/construction workers/city sanitation workers, etc.)
( ) Company employees
( ) Career/civil servants/government workers
( ) Students
( ) Housewife
( ) No job/retired

4. Educational level [Single-choice]

( ) High school and below
( ) College
( ) Undergraduate
( ) Graduate

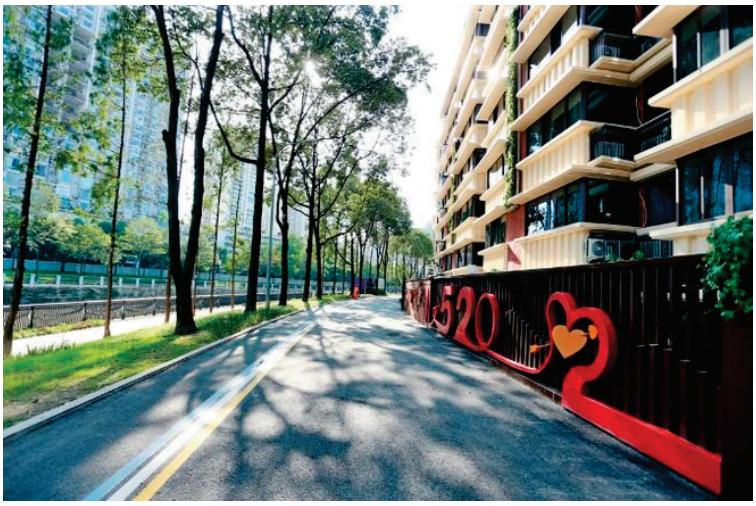
5. Whether or not to hold a driver's license [radio]

( ) Yes
( ) No

6. Your monthly income [Single-choice]

( ) Less than 1500 RMB
( ) 1500–3500 RMB
( ) 3500–4500 RMB
( ) 4500–8000 RMB
( ) 8000–15,000 RMB
( ) Above 15,000 RMB

7. Preferred environment for walking [Single-choice]



( ) Community Street

( ) Waterfront path

( ) Urban Greenway

8. How do you think the presence of infrastructure on streets physical environmental factors of infrastructure affects your choice of that road as a walking path? (A higher negative value means less likely to choose the path, a higher positive value means more likely to choose the path, 0 means no effect) [Matrix scale question]

**Table A1.** Preferences for streets physical environmental factors of infrastructure.

| Environmental Factors | Score | | | | | | |
|---|---|---|---|---|---|---|---|
| | **−3** | **−2** | **−1** | **0** | **1** | **2** | **3** |
| Streetlights and lighting facilities | | | | | | | |
| Guardrails | | | | | | | |
| Signage | | | | | | | |
| Garbage cans | | | | | | | |
| Wire poles | | | | | | | |
| Billboards | | | | | | | |
| Street cameras | | | | | | | |
| High voltage boxes | | | | | | | |
| Retail stores | | | | | | | |
| Restaurants | | | | | | | |
| Teahouses | | | | | | | |
| Bars | | | | | | | |
| Cafés | | | | | | | |
| Internet cafes | | | | | | | |
| Food markets/hypermarkets | | | | | | | |
| Mobile stalls | | | | | | | |
| Toilets | | | | | | | |
| Community clinics/hospitals | | | | | | | |
| Community fitness equipment | | | | | | | |
| Community service centers | | | | | | | |
| Bus Stations | | | | | | | |
| Subway Stations | | | | | | | |
| Cab stands | | | | | | | |
| Bicycle parking | | | | | | | |

9. How do you think the presence of streets physical environmental factors of walking conditions affects your choice of that road as a walking path? (A higher negative value means less likely to choose the path, a higher positive value means more likely to choose the path, 0 means no effect) [Matrix scale question]

**Table A2.** Preferences for streets physical environmental factors of walking conditions.

| Environmental Factors | Score | | | | | | |
|---|---|---|---|---|---|---|---|
| | **−3** | **−2** | **−1** | **0** | **1** | **2** | **3** |
| Traffic signals | | | | | | | |
| Crossroads | | | | | | | |
| Ramps | | | | | | | |
| Sidewalks | | | | | | | |
| Pedestrian bridges | | | | | | | |
| Underpasses | | | | | | | |
| Level ground | | | | | | | |
| Ground paving | | | | | | | |
| Road greenery | | | | | | | |

10. How do you think the presence of streets physical environmental factors of environmental quality affects your choice of that road as a walking path? (A higher negative value means less likely to choose the path, a higher positive value means more likely to choose the path, 0 means no effect) [Matrix scale question]

**Table A3.** Preferences for streets physical environmental factors of environmental quality.

| Environmental Factors | Score | | | | | | |
|---|---|---|---|---|---|---|---|
| | −3 | −2 | −1 | 0 | 1 | 2 | 3 |
| Road greenery | | | | | | | |
| Green space along the street | | | | | | | |
| Artificial landscape | | | | | | | |
| Litter on the street | | | | | | | |
| Seating | | | | | | | |
| Gazebo | | | | | | | |
| Fountain | | | | | | | |
| Tree pond with seating | | | | | | | |

11. How do you think the presence of the streets s aesthetic environmental factors affects your choice of that road as a walking path? (A higher negative value means less likely to choose the path, a higher positive value means more likely to choose the path, 0 means no effect) [Matrix Scale Questions]

**Table A4.** Preferences for streets aesthetic environmental factors.

| Dimension | Environmental Factors | Score | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | −3 | −2 | −1 | 0 | 1 | 2 | 3 |
| Subjective perception | Diversity | | | | | | | |
| | Convenience | | | | | | | |
| | Uniformity | | | | | | | |
| | Novelty | | | | | | | |
| | Maintainability | | | | | | | |
| | Charm | | | | | | | |
| | Sense of mystery | | | | | | | |
| Sensory perception | Pleasant sounds | | | | | | | |
| | Noise | | | | | | | |
| | Pleasant odors | | | | | | | |

## References


1. Wang, R.; Liu, Y.; Lu, Y.; Zhang, J.; Liu, P.; Yao, Y.; Grekousis, G. Perceptions of built environment and health outcomes for older Chinese in Beijing: A big data approach with street view images and deep learning technique. *Comput. Environ. Urban Syst.* **2019**, *78*, 101386. [CrossRef]
2. Cao, X.Y.; Handy, S.L.; Mokhtarian, P.L. The influences of the built environment and residential self-selection on pedestrian behavior: Evidence from Austin, TX. *Transportation* **2006**, *33*, 1–20. [CrossRef]
3. Handy, S.; Cao, X.Y.; Mokhtarian, P. Correlation or causality between the built environment and travel behavior? Evidence from Northern California. *Transp. Res. D Transp. Environ.* **2005**, *10*, 427–444. [CrossRef]
4. Saelens, B.E.; Handy, S.L. Built environment correlates of walking: A review. *Med. Sci. Sport. Exerc.* **2008**, *40*, S550–S566. [CrossRef]
5. Merriman, P. Driving places—Marc Auge, non-places, and the geographies of England's M1 motorway. *Theory Cult. Soc.* **2004**, *21*, 145–167. [CrossRef]
6. Constitution of the World Health Organization. Available online: https://apps.who.int/gb/bd/PDF/bd47/EN/constitution-en.pdf?ua=1 (accessed on 30 March 2023).
7. Kan, Z.; Kwan, M.-P.; Ng, M.K.; Tieben, H. The Impacts of Housing Characteristics and Built-Environment Features on Mental Health. *Int. J. Environ. Res. Public Health* **2022**, *19*, 5143. [CrossRef]

8. Frank, L.D.; Engelke, P. Multiple impacts of the built environment on public health: Walkable places and the exposure to air pollution. *Int. Reg. Sci. Rev.* **2005**, *28*, 193–216. [CrossRef]
9. Zhai, Y.; Baran, P.K. Urban park pathway design characteristics and senior walking behavior. *Urban For. Urban Green.* **2017**, *21*, 60–73. [CrossRef]
10. Frank, L.D.; Engelke, P.O. The built environment and human activity patterns: Exploring the impacts of urban form on public health. *J. Plan. Lit.* **2001**, *16*, 202–218. [CrossRef]
11. Sundquist, K.; Eriksson, U.; Kawakami, N.; Skog, L.; Ohlsson, H.; Arvidsson, D. Neighborhood walkability, physical activity, and walking behavior: The Swedish Neighborhood and Physical Activity (SNAP) study. *Soc. Sci. Med.* **2011**, *72*, 1266–1273. [CrossRef]
12. Van Holle, V.; Deforche, B.; Van Cauwenberg, J.; Goubert, L.; Maes, L.; Van de Weghe, N.; De Bourdeaudhuij, I. Relationship between the physical environment and different domains of physical activity in European adults: A systematic review. *BMC Public Health* **2012**, *12*, 807. [CrossRef]
13. Saelens, B.E.; Sallis, J.F.; Frank, L.D. Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. *Ann. Behav. Med.* **2003**, *25*, 80–91. [CrossRef]
14. Hillsdon, M.; Thorogood, M.; Anstiss, T.; Morris, J. Randomized Controlled Trials of Physical-Activity Promotion in Free-Living Populations—A Review. *J. Epidemiol. Community Health* **1995**, *49*, 448–453. [CrossRef]
15. Lee, I.-M.; Paffenbarger, R.S., Jr. Associations of Light, Moderate, and Vigorous Intensity Physical Activity with Longevity: The Harvard Alumni Health Study. *Am. J. Epidemiol.* **2000**, *151*, 293–299. [CrossRef]
16. Baker, G.; Gray, S.R.; Wright, A.; Fitzsimons, C.; Nimmo, M.; Lowry, R.; Mutrie, N.; Scottish Phys Activity Res, C. The effect of a pedometer-based community walking intervention "Walking for Wellbeing in the West" on physical activity levels and health outcomes: A 12-week randomized controlled trial. *Int. J. Behav. Nutr. Phys. Act.* **2008**, *5*, 44. [CrossRef]
17. Morris, J.N.; Hardman, A.E. Walking to health. *Sport. Med.* **1997**, *23*, 306–332. [CrossRef]
18. Kelly, P.; Murphy, M.; Mutrie, N. The Health Benefits of Walking. *Walking* **2017**, *9*, 61–79.
19. Evenson, K.R.; Eyler, A.A.; Wilcox, S.; Thompson, J.L.; Burke, J.E. Test-retest reliability of a questionnaire on physical activity and its correlates among women from diverse racial and ethnic groups. *Am. J. Prev. Med.* **2003**, *25*, 15–22. [CrossRef]
20. Lee, I.M.; Buchner, D.M. The importance of walking to public health. *Med. Sci. Sports Exerc.* **2008**, *40*, S512–S518. [CrossRef]
21. Krogh, C.M.E.; Gillis, L.; Kouwen, N.; Aramini, J. WindVOiCe, a Self-Reporting Survey: Adverse Health Effects, Industrial Wind Turbines, and the Need for Vigilance Monitoring. *Bull. Sci. Technol. Soc.* **2011**, *31*, 334–345. [CrossRef]
22. Prohaska, T.R.; Eisenstein, A.R.; Satariano, W.A.; Hunter, R.; Bayles, C.M.; Kurtovich, E.; Kealey, M.; Ivey, S.L. Walking and the Preservation of Cognitive Function in Older Populations. *Gerontologist* **2009**, *49*, S86–S93. [CrossRef] [PubMed]
23. Schubert, C.R.; Fischer, M.E.; Pinto, A.A.; Klein, B.E.K.; Klein, R.; Tweed, T.S.; Cruickshanks, K.J. Sensory Impairments and Risk of Mortality in Older Adults. *J. Gerontol. A Biol. Sci. Med. Sci.* **2017**, *72*, 710–715. [CrossRef] [PubMed]
24. Trudeau, D. A typology of New Urbanism neighborhoods. *J. Urban. Int. Res. Placemaking Urban Sustain.* **2013**, *6*, 113–138. [CrossRef]
25. Li, Y.; Peng, L.; Wu, C.; Zhang, J. Street View Imagery (SVI) in the Built Environment: A Theoretical and Systematic Review. *Buildings* **2022**, *12*, 1167. [CrossRef]
26. Talen, E. Do-it-Yourself Urbanism:A History. *J. Plan. Hist.* **2015**, *14*, 135–148. [CrossRef]
27. Sallis, J.F.; Floyd, M.F.; Rodriguez, D.A.; Saelens, B.E. Role of Built Environments in Physical Activity, Obesity, and Cardiovascular Disease. *Circulation* **2012**, *125*, 729–737. [CrossRef]
28. Durand, C.P.; Andalib, M.; Dunton, G.F.; Wolch, J.; Pentz, M.A. A systematic review of built environment factors related to physical activity and obesity risk: Implications for smart growth urban planning. *Obes. Rev.* **2011**, *12*, e173–e182. [CrossRef]
29. Sallis, J.F.; Cerin, E.; Conway, T.L.; Adams, M.A.; Frank, L.D.; Pratt, M.; Salvo, D.; Schipperijn, J.; Smith, G.; Cain, K.L.; et al. Physical activity in relation to urban environments in 14 cities worldwide: A cross-sectional study. *Lancet* **2016**, *387*, 2207–2217. [CrossRef]
30. Olszewski, P.; Wibowo, S.S. Using Equivalent Walking Distance to Assess Pedestrian Accessibility to Transit Stations in Singapore. *Transp. Res. Rec.* **2005**, *1927*, 38–45. [CrossRef]
31. Guo, Z.; Loo, B.P.Y. Pedestrian environment and route choice: Evidence from New York City and Hong Kong. *J. Transp. Geogr.* **2013**, *28*, 124–136. [CrossRef]
32. Borst, H.C.; de Vries, S.I.; Graham, J.M.A.; van Dongen, J.E.F.; Bakker, I.; Miedema, H.M.E. Influence of environmental street characteristics on walking route choice of elderly people. *J. Environ. Psychol.* **2009**, *29*, 477–484. [CrossRef]
33. Muraleetharan, T.; Hagiwara, T. Overall level of service of urban walking environment and its influence an pedestrian route choice behavior—Analysis of pedestrian travel in Sapporo, Japan. *Transp. Res. Rec.* **2007**, *2002*, 7–17. [CrossRef]
34. Broach, J.; Dill, J. Pedestrian Route Choice Model Estimated from Revealed Preference GPS Data. In Proceedings of the Transportation Research Board 94th Annual Meeting, Washington, DC, USA, 11–15 January 2015.
35. Siregar, A. Aesthetics of the Street Environment and the Link to Street Activity. Master's Thesis, University of Leeds, Leeds, UK, 2011.
36. Smardon, R.C. Perception and Aesthetics of the Urban-Environment—Review of the Role of Vegetation. *Landsc. Urban Plan.* **1988**, *15*, 85–106. [CrossRef]
37. Danaci, H.M.; Kiran, G.S. Examining the Factor of Color on Street Facades in Context of the Perception of Urban Aesthetics: Example of Antalya. *Int. J. Curric. Instr.* **2020**, *12*, 222–232.

38. Folkmann, M.N. Evaluating Aesthetics in Design: A Phenomenological Approach. *Des. Issues* **2010**, *26*, 40–53. [CrossRef]
39. Ball, K.; Bauman, A.; Leslie, E.; Owen, N. Perceived environmental aesthetics and convenience and company are associated with walking for exercise among Australian adults. *Prev. Med.* **2001**, *33*, 434–440. [CrossRef]
40. Ellaway, A.; Macintyre, S.; Bonnefoy, X. Graffiti, greenery, and obesity in adults: Secondary analysis of European cross sectional survey. *BMJ Br. Med. J.* **2005**, *331*, 611–612. [CrossRef]
41. Handy, S.L.; Boarnet, M.G.; Ewing, R.; Killingsworth, R.E. How the built environment affects physical activity—Views from urban planning. *Am. J. Prev. Med.* **2002**, *23*, 64–73. [CrossRef]
42. Ewing, R.; Handy, S. Measuring the Unmeasurable: Urban Design Qualities Related to Walkability. *J. Urban Des.* **2009**, *14*, 65–84. [CrossRef]
43. Koo, B.W.; Guhathakurta, S.; Botchwey, N. How are Neighborhood and Street-Level Walkability Factors Associated with Walking Behaviors? A Big Data Approach Using Street View Images. *Environ. Behav.* **2022**, *54*, 211–241. [CrossRef]
44. Zhao, J.; Xu, W.; Ye, L. Effects of auditory-visual combinations on perceived restorative potential of urban green space. *Appl Acoust* **2018**, *141*, 169–177. [CrossRef]
45. Koh, P.P.; Wong, Y.D. Comparing pedestrians' needs and behaviours in different land use environments. *J. Transp. Geogr.* **2013**, *26*, 43–50. [CrossRef]
46. Hong, X.-C.; Cheng, S.; Liu, J.; Dang, E.; Wang, J.-B.; Cheng, Y. The Physiological Restorative Role of Soundscape in Different Forest Structures. *Forests* **2022**, *13*, 1920. [CrossRef]
47. Hong, X.-C.; Liu, J.; Wang, G.-Y. Soundscape in Urban Forests. *Forests* **2022**, *13*, 2056. [CrossRef]
48. Montello, D.R.; Goodchild, M.F.; Gottsegen, J.; Fohl, P. Where's Downtown?: Behavioral Methods for Determining Referents of Vague Spatial Queries. *Spat. Cogn. Comput.* **2003**, *3*, 185–204. [CrossRef]
49. Creswell, J.W.; Creswell, J.D. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 3rd ed.; SAGE Publications: London, UK, 2018.
50. Long, Y.; Wu, K.; Mao, Q. Simulating Urban Expansion in the Parcel Level for All Chinese Cities. *arXiv* **2014**, arXiv:1402.3718.
51. Zhong, Q.; Li, B.; Chen, Y. How Do Different Urban Footpath Environments Affect the Jogging Preferences of Residents of Different Genders? Empirical Research Based on Trajectory Data. *Int. J. Environ. Res. Public Health* **2022**, *19*, 14372. [CrossRef]
52. Davies, J.S. The governance of urban regeneration: A critique of the 'governing without government' thesis. *Public Adm.* **2002**, *80*, 301–322. [CrossRef]
53. Miranda, A.S.; Fan, Z.; Duarte, F.; Ratti, C. Desirable streets: Using deviations in pedestrian trajectories to measure the value of the built environment. *Comp. Env. Urban Syst.* **2021**, *86*, 101563. [CrossRef]
54. Guo, Z. Does the pedestrian environment affect the utility of walking? A case of path choice in downtown Boston. *Trans. Res. Part D Tran. Environ.* **2009**, *14*, 343–352. [CrossRef]
55. Alves, S.; Aspinall, P.A.; Ward Thompson, C.; Sugiyama, T.; Brice, R.; Vickers, A. Preferences of older people for environmental attributes of local parks. *Facilities* **2008**, *26*, 433–453. [CrossRef]
56. Niu, X.; Wu, W.; Li, M. Influence of Built Environment on Street Vitality and Its Spatiotemporal Characteristics Based on LBS Positioning Data. *Urban Plan. Int.* **2019**, *34*, 28–37. [CrossRef]
57. Seneviratne, P.N.; Morrall, J.F. Analysis of factors affecting the choice of route of pedestrians. *Trans. Plan. Technol.* **1985**, *10*, 147–159. [CrossRef]
58. Hauru, K.; Koskinen, S.; Kotze, D.J.; Lehvavirta, S. The effects of decaying logs on the aesthetic experience and acceptability of urban forests—Implications for forest management. *Landsc. Urban Plan.* **2014**, *123*, 114–123. [CrossRef]
59. Blumentrath, C.; Tveit, M.S. Visual characteristics of roads: A literature review of people's perception and Norwegian design practice. *Trans. Res. Part A Policy Pract.* **2014**, *59*, 58–71. [CrossRef]
60. Coeterier, J.F. Dominant attributes in the perception and evaluation of the Dutch landscape. *Landsc. Urban Plan.* **1996**, *34*, 27–44. [CrossRef]
61. Peschardt, K.K.; Stigsdotter, U.K. Associations between park characteristics and perceived restorativeness of small public urban green spaces. *Landsc. Urban Plan.* **2013**, *112*, 26–39. [CrossRef]
62. Mesimaki, M.; Hauru, K.; Kotze, D.J.; Lehvavirta, S. Neo-spaces for urban livability? Urbanites' versatile mental images of green roofs in the Helsinki metropolitan area, Finland. *Land Use Policy* **2017**, *61*, 587–600. [CrossRef]
63. Chen, B.; Adimo, O.A.; Bao, Z. Assessment of aesthetic quality and multiple functions of urban green space from the users' perspective: The case of Hangzhou Flower Garden, China. *Landsc. Urban Plan.* **2009**, *93*, 76–82. [CrossRef]
64. Kirillova, K.; Fu, X.; Lehto, X.; Cai, L. What makes a destination beautiful? Dimensions of tourist aesthetic judgment. *Tour. Manag.* **2014**, *42*, 282–293. [CrossRef]
65. Hattie, J. Methodology Review—Assessing Unidimensionality of Tests and Items. *Appl. Psych. Meas.* **1985**, *9*, 139–164. [CrossRef]
66. Landis, J.R.; Koch, G.G. The Measurement of Observer Agreement for Categorical Data. *Biometrics* **1977**, *33*, 159–174. [CrossRef] [PubMed]
67. Handy, S.; Cao, X.Y.; Mokhtarian, P.L. Self-selection in the relationship between the built environment and walking—Empirical evidence from northern California. *J. Am. Plann. Assoc.* **2006**, *72*, 55–74. [CrossRef]
68. Sahani, R.; Bhuyan, P.K. Pedestrian Level of Service Criteria for Urban Off-Street Facilities in Mid-Sized Cities. *Transport* **2017**, *32*, 221–232. [CrossRef]

69. Caesarina, H.M.; Humaida, N.; Amali, M.F.; Wahyudi, M.W. The Need of Green Open Spacesa as the Effect of Urban Waterfront Development in Sungai Bilu, a Stream Corridor Neighbourhood in Banjarmasin. In Proceedings of the 5th International Conference on Sustainable Built Environment (ICSBE)—Management of Changes for Livable Environment, Banjarmasin, Indonesia, 11–13 October 2019.
70. Saito, Y. Future Directions for Environmental Aesthetics. *Environ. Value* **2010**, *19*, 373–391. [CrossRef]
71. Guo, X.; Liu, J.; Chen, Z.; Hong, X.-C. Harmonious Degree of Sound Sources Influencing Visiting Experience in Kulangsu Scenic Area, China. *Forests* **2023**, *14*, 138. [CrossRef]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

MDPI AG
Grosspeteranlage 5
4052 Basel
Switzerland
Tel.: +41 61 683 77 34

MDPI Books Editorial Office
E-mail: books@mdpi.com
www.mdpi.com/books

Disclaimer/Publisher's Note: The title and front matter of this reprint are at the discretion of the Topic Editors. The publisher is not responsible for their content or any associated concerns. The statements, opinions and data contained in all individual articles are solely those of the individual Editors and contributors and not of MDPI. MDPI disclaims responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

Academic Open
Access Publishing

mdpi.com

ISBN 978-3-7258-4094-6