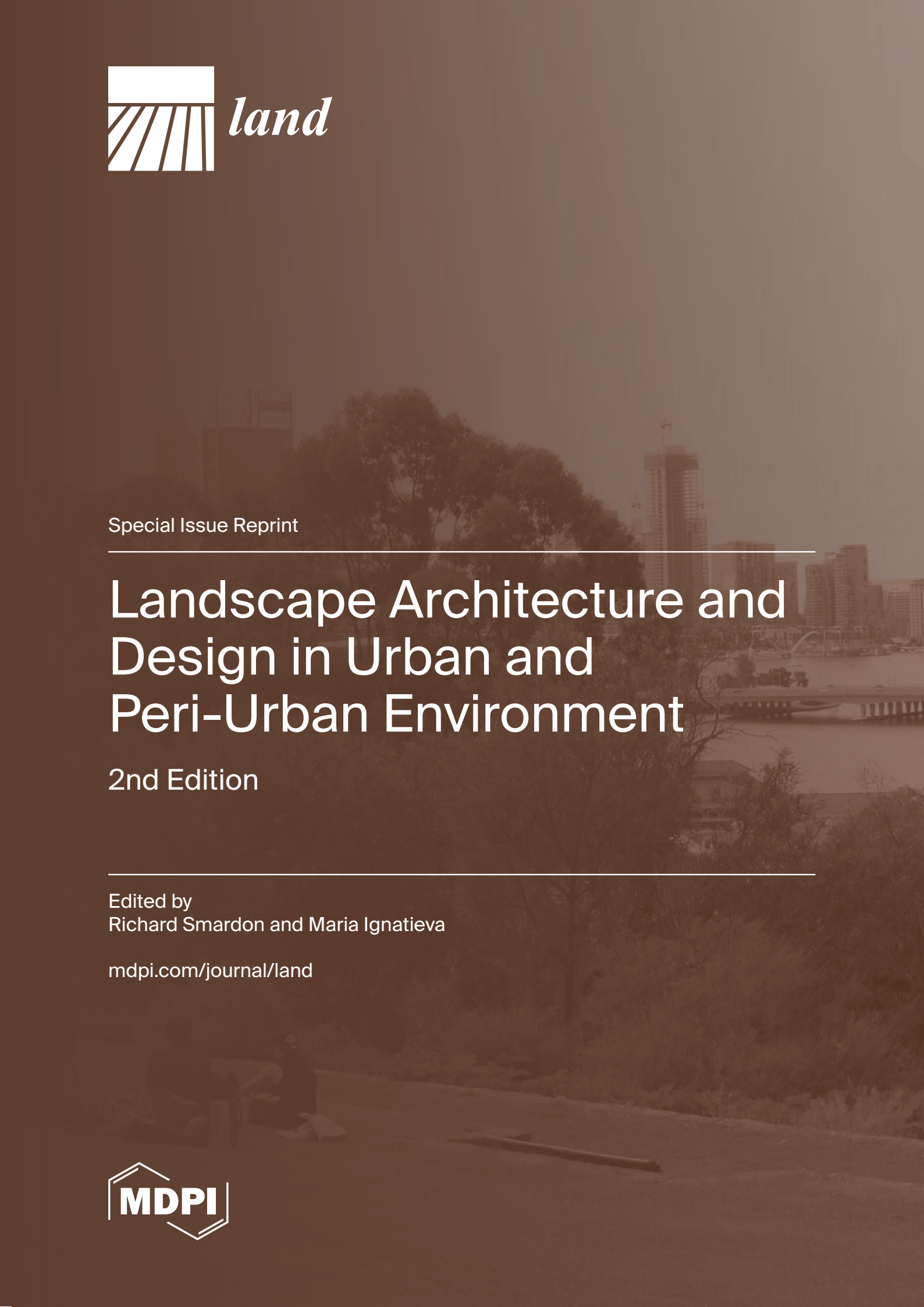


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Special Issue Reprint

Landscape Architecture and Design in Urban and Peri-Urban Environment

2nd Edition

Edited by
Richard Smardon and Maria Ignatieva

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Landscape Architecture and Design in Urban and Peri-Urban Environment: 2nd Edition

Landscape Architecture and Design in Urban and Peri-Urban Environment: 2nd Edition

Guest Editors

Richard Smardon
Maria Ignatieva

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Kings Park and Botanic Garden, Perth, Western Australia

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About the Editors

Richard Smardon

Richard Smardon is a SUNY Distinguished Service Professor Emeritus at SUNY College of Environmental Science and Forestry. He has edited/written eight books, with the most recent being *The Renewable Energy Landscape* (2017), *Revitalizing Urban Waterway Communities*; *Streams of Environmental Justice* (2018) and *Education for Sustainable Human and Environmental Systems* (2019.) He has edited four *Land* journal Special Issue Reprints including "Selected Papers from the 6th Fabos Conference on Landscape and Greenway Planning and Landscape Architecture Research" and "Design for Urban and Peri-Urban Environment" (1st edition). He co-produced the 2019 and 2021 Visual Resource Stewardship conferences and co-edited the 2017 Visual Resource Stewardship conference proceedings.

Maria Ignatieva

Maria Ignatieva is a Professor of Landscape Architecture at the School of Design, University of Western Australia. She has worked in five countries (in Europe, the USA, Australia and New Zealand), teaching as a full-time tenured academic in landscape architecture programs, conducting research in urban ecology (urban biodiversity and design), green infrastructure, nature-based solutions, the history of landscape architecture and garden restoration, and implementing research results in practical landscape architecture projects. She is the recipient of the 2024 IFLA (International Federation of Landscape Architects) President's Award, and the President of URBIO (Urban Biodiversity and Design International).

Preface

This is a Reprint of the *Land* journal Special Issue with the topic of "Landscape Architecture Research and Design for Urban and Peri-Urban Environments". Articles within the Special Issue can be grouped within the subtopics of (1) urban environmental health and safety, (2) urban agricultural and land use assessment, (3) streetscape assessment and development, (4) urban vegetation and plant biodiversity, and (5) urban climate assessment and mitigation.

Richard Smardon and Maria Ignatieva
Guest Editors

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Editorial

Overview of "Landscape Research and Design for Urban and Peri-Urban Environments—2nd Edition"

Maria Ignatieva [1] and Richard Smardon [2,*]

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1. Introduction

This is a continuation on the theme of the first edition of this Special Issue of *Land*, "Landscape Research and Design for the Urban and Peri-Urban Environments", edited by Richard Smardon [1]. There is a pressing need for landscape architecture and design research to address rapid urbanization and its impacts on urban and peri-urban environments. The constant sprawl of urban areas, and the mitigation thereof, sets an imperative to better understand which natural and man-made landscape innovations or patterns in urban landscape architecture and design are most suitable and sustainable. Such knowledge is crucial to achieving sustainable urbanization while maintaining and improving urban and peri-urban landscapes, and providing healthy environments for urban residents.

Thus, innovative research that is supported by computational approaches, field studies, successful landscape architecture case studies, and spatial analyses seeking to expand knowledge on sustainable urbanization is in high demand. In this Special Issue, we invited researchers to share their work on combining state-of-the-art landscape architecture and design with sustainable solutions, as well as other research fields such as environmental health, urban agriculture and land use, urban flora and vegetation, streetscape design, and urban climate mitigation, in addition to architectural and design amenities related to urban and peri-urban environmental engineering fostering resilience to the impacts of urbanization.

We welcomed manuscripts that addressed the following themes: peri-urban landscape restoration; sustainable landscape architecture, planning, design, and management of public open spaces and green spaces; sustainable urban design; planning and maintenance of peri-urban areas; expansion of urban areas and their impact in an urban–rural context; and enhancement of environmental and human health benefits.

2. Key Findings and Insights

The articles in this Special Issue fall into five major categories: (1) urban environmental health and safety, (2) urban agricultural and land use assessment, (3) streetscape assessment and development, (4) urban vegetation and plant biodiversity assessment, and (5) urban climate assessment and mitigation. Each of these thematic areas will be summarized in that order.

Yang et al.'s article (Contribution 1) investigated associations between facility accessibility and resident health in new rural communities in China. Gheitasi et al. (Contribution 7) evaluated the impact of an oil refinery in Tehran on the landscape perception and mental health of nearby residents. Nosrati et al. (Contribution 9) investigated the greenspace

design of small inner-city parks and how it impacts teenager stress levels in New Zealand. Zhao et al. (Contribution 12) assessed visitor usage and the safety perceptions of people visiting Chinese National Forest Parks. All of these articles contribute to the development of the methods used to assess people's perceptions of environmental health and safety.

Under the second theme, urban agricultural and land use assessment, Zeunert et al. (Contribution 2) explored the role urban agriculture plays in land use planning in the Greater Sydney region, Australia, utilizing GIS data. Xie et al. (Contribution 13) investigated environmental management and landscape design for "lifestyle blocks" in peri-urban communities in New Zealand. Both studies relied on the innovative use of spatial data to project possible future land use development configurations.

For the third theme, urban streetscape assessment, Lu et al. (Contribution 3) assessed the combined effects of sound and vision on subjects perceiving the restoration of four streetscape types in Nanjing, China. Clemente (Contribution 5) focused on the impact of street trees on sidewalks and streetscape redevelopment in Rome, Italy. Marshall et al. (Contribution 8) assessed the role street furniture plays in improving the design and amenities of open public spaces. Bai et al. (Contribution 11) investigated motorists' perceptions of scenic roads in peri-urban Malaysia using binocular simulation and image segmentation methodology. Although these four studies are quite different methodologically, they all offer innovative ways of assessing linear urban landscapes.

The fourth theme was urban vegetation and biodiversity assessment. Stewart and Ignatieva (Contribution 4) present a case study for assessing the functions of spontaneous vegetation in Southwestern Australian cities. Davidová et al. (Contribution 6) offer the use of gamification as a means to gather reactions and evaluations of greenspace enhancements and alternative designs. Li and Gou (Contribution 10) assess nature-based solutions to manage urban flooding in United States urban parks. Lee et al. (Contribution 14) present a comprehensive literature review of spatial dimension measurements for urban green space research and development. All of these articles provide a rich base of research that can assist with future greenspace assessment and development.

The final and fifth theme of this Special Issue is urban climate mitigation. Norouzi et al. (Contribution 15) offer a review of design- and site-related factors affecting the cooling performance or urban parks in different climatic zones. Nikologianni and Albans (Contribution 16) present another review article on landscape design and policy climate guidance. Both review articles offer a solid foundation for addressing research needs pertaining to urban climate mitigation.

3. Conclusions

The sixteen articles that make up this Special Issue all contribute urban and peri-urban landscape research and development that complements existing guides for research and design in this context [1–3].

Author Contributions: Conceptualization, R.S. and M.I.; writing—original draft preparation, R.S.; writing—review and editing, R.S. and M.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors and editors of the this Special Issue of *Land* on "Landscape Architecture Research and Design for Urban and Peri-Urban Environment—2nd Edition" wish to thank the contributing authors as well as the editorial staff of *Land* who supported the production of this Special Issue. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

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1. Yang, X.; Liu, C.; Liu, W.; Hu, X.; Li, K. Analysis of the Correlation Between the Accessibility of Built Environment Elements and Residents' Self-Rated Health in New Rural Communities. *Land* **2025**, *14*, 1867. https://doi.org/10.3390/land14091867.
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14. Lee, D.H.; Chamberlain, B.; Park, H.Y. Toward a Construct-Based Definition of Urban Green Space: A Literature Review of the Spatial Dimensions of Measurement, Methods, and Exposure. *Land* **2025**, *14*, 517. https://doi.org/10.3390/land14030517.
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Article

Evaluating Visitor Usage and Safety Perception Experiences in National Forest Parks

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Abstract: Various physical and environmental factors affect the recreational experience in national forest parks. Understanding visitors' preferences regarding these factors is significant for promoting the physical and mental health and well-being of urban residents. This study aims to quantify residents' usage patterns and safety perceptions of national forest parks. It focuses particularly on Santai Mountain National Forest Park in Jiangsu, China, and conducted a semi-structured questionnaire survey with 688 participants. The statistical software IBM SPSS Statistics 24 was used for data analysis. A descriptive quantitative analysis was conducted on the respondents' demographic information. Descriptive statistics, chi-square tests, and an ordinal logistic regression model were employed to analyze the survey data. The survey results show that most visitors go to the forest park only once or twice a year, usually on weekends, holidays, and during leisure time rather than on workdays. Because the national forest park is located in the suburbs, the journey is long, and most visitors choose to drive there. Additionally, the majority of visitors go to the forest park with family and friends. Because the park is well managed and has complete safety facilities, most visitors feel safe in the national forest park.

Keywords: national forest park; green space; park usage; park safety; accessibility; sustainability

1. Introduction

National forest parks (NFPs) are a critical component of the forest parks system, featuring distinctive scenery, valuable social resources, and a healthy ecosystem. Numerous studies have highlighted the various advantages they offer, making them essential elements of urban environments and contributing to the physical and mental well-being of individuals [1,2]. Forest parks provide several benefits to urban ecosystems, such as controlling air quality [3], regulating the climate, capturing carbon dioxide, reducing atmospheric pollution, releasing abundant oxygen, purifying water, replenishing water supplies, reducing noise [4], and preserving biodiversity [5]. Commonly referred to as "the lung of the city" and "the oxygen bar of the city," NFPs play a significant role in reducing psychological stress, including anxiety, promoting emotional well-being, and enhancing both mental and physical health [6]. Furthermore, NFPs help mitigate the urban heat island effect, contributing to cooler city climates [7].

Urban residents can only enjoy the benefits of parks if they have reasonable access to them [8,9]. Numerous studies conducted in various cities worldwide have examined the impact of elements such as distance and time spent traveling [3], park users' socioeconomic backgrounds [3,10], and park features [1,2] on park accessibility. However, there has been a lack of distinction between forest parks and city parks, despite significant differences in their location, landscape, activities, and scope of services. Additionally, there is limited research exploring the factors that drive demand, and to the best of our understanding, no investigations have been conducted in China. As an outcome, our study aims to

bridge this gap by concentrating specifically on the differences in park use between forest parks and other urban parks. If the quality of green space is important to spots, then the nature of urban parks is an important factor to consider. For example, the size of parks and accessibility have a strong connection to park use and a boost in people's activity levels [11].

One of the most significant variables for explaining park utilization by urban dwellers is park accessibility, which can be categorized into two distinct groups: real accessibility and prospective accessibility [12]. The first type emphasizes the utilization of natural environments, while the other focuses on the quantity of natural surroundings available in a specific area. The distance and duration of a trip are typical variables used to quantify accessibility, a concept rooted in Location Theory and Central Place Theory [13]. To account for the possibility of the impact of socio-personal features on the capacity to access services, accessibility was defined as the ease with which individuals can reach their chosen activity areas. Judgments of park accessibility are strongly influenced by both park characteristics and the sociodemographic variables of park users. In a similar vein, additional variables influencing accessibility include the quantity and quality of available space, the socioeconomic background of users, the proximity to competing amenities, the capacity of facilities to meet user demands, the quality of facility maintenance, and the perceived safety of the facilities offered [14]. Other research confirms that the utilization of green spaces is influenced by various factors, particularly the proximity, quality, and quantity of available green areas [15]. The demand for ecological services is significantly influenced by socioeconomic and demographic characteristics [11]. Other studies primarily focus on the sociodemographic traits of park users, including factors such as race, gender, age, and income, which all play a significant role in park and greenspace utilization, as documented in existing research [16]. Certain academic studies indicate that people of color and those with lower incomes are more likely to have limited access to parks [17]. Furthermore, some studies investigate the accessibility of urban parks for children, revealing potential issues related to equity and environmental justice [18,19]. National forest parks are not universally present, which highlights a limitation of this study. Countries and regions such as mainland China [3,20,21], Taiwan [5], the Czech Republic [22], and the United States [23] have these parks.

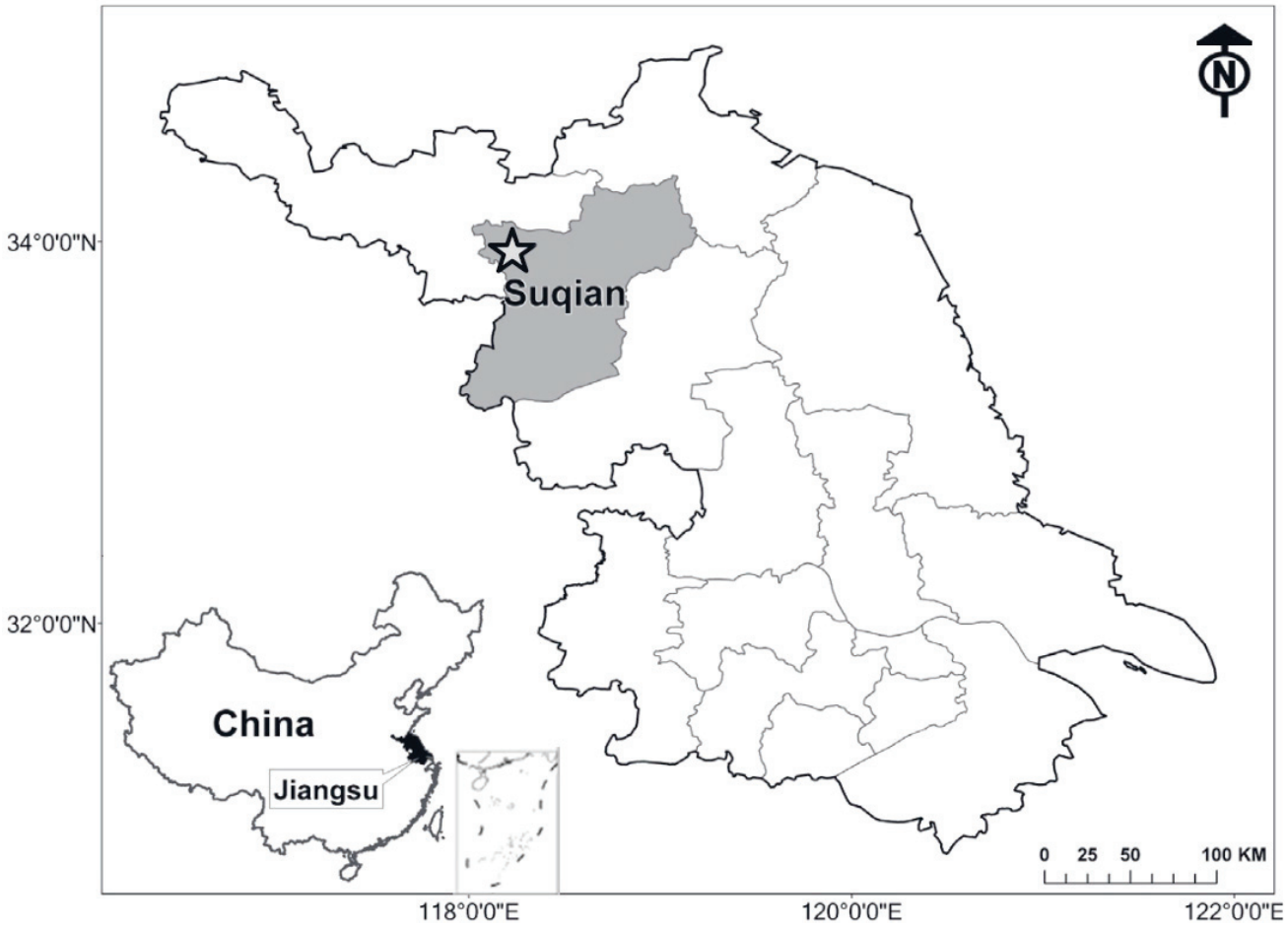
Currently, research on the use of NFPs is predominantly concentrated in Europe and North America, with significantly fewer studies in Asia, particularly in China. This is especially true for studies on the use and safety of NFPs. Previous research has primarily focused on the impact of environmental characteristics and user behavior on the use of NFPs. However, there is a notable lack of systematic analysis from a socio-ecological perspective, especially regarding the influence of different sociodemographic characteristics (such as gender, household registration, age, education level, marital status, and occupation) on the leisure experiences of NFP visitors. Consequently, this study aims to address these gaps by incorporating sociodemographic factors into the examination of leisure experiences in NFPs. This study has three main objectives: (1) to evaluate visitors' usage patterns of NFPs; (2) to explore the safety factors associated with visitors' use of NFPs; and (3) to provide guidance for the future planning and design of NFPs, thereby enhancing their recreational value and promoting their sustainable development.

2. Materials and Methods

2.1. Study Site

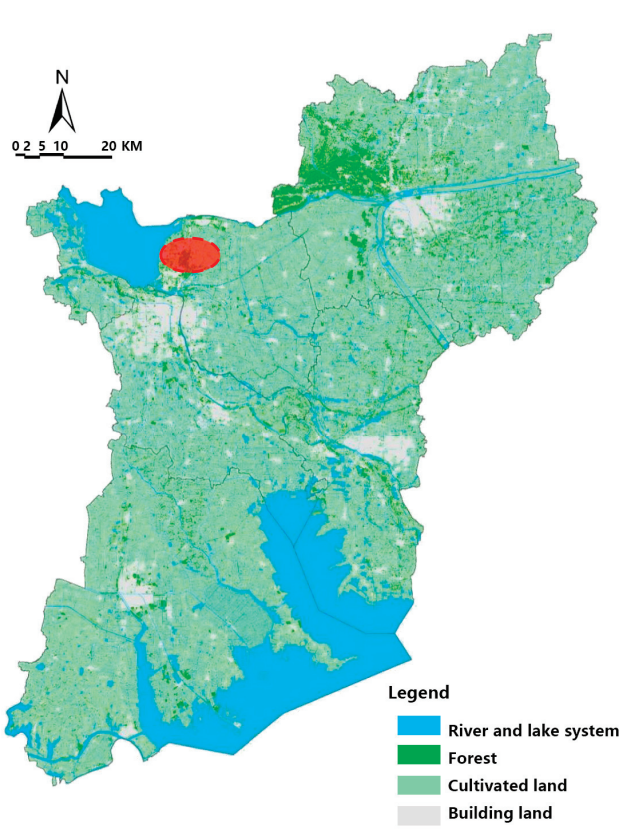
Suqian is located in the north of Jiangsu Province and in the eastern part of the map of China (refer to Figure 1). The city experiences a warm temperate monsoon climate, located between 33°12′17″–34°24′38″ north latitude and 117°6′19″–119°12′50″ east longitude [24]. It includes 4603 square kilometers of arable land and 2198 square kilometers of water surface [24]. Santai Mountain NFP is located near the Lakeside New District of Suqian City, Jiangsu Province, on the shore of Luoma Lake. Situated 7 km north of the city center, the park covers an area of 1270 hectares and serves as the central city's "oxygen

bar" and "back garden," with a forest coverage rate of 98% [25]. The forest park boasts a remarkable concentration of 20,000 negative oxygen ions per cubic centimeter and offers a comprehensive range of attractions, including forest landscapes, natural scenery, cultural and artistic experiences, and forest-based leisure and vacation activities (refer to Figure 2). According to the official website of the Suqian Municipal People's Government [24], the park provides natural landscape tourism, cultural and artistic experiences, forest leisure and holiday activities, science education, and sports fitness (refer to Figure 3).



(**a**)

Figure 1. *Cont*.



(**b**)



(**c**)

Figure 1. Location of the study area and the NFP. The map depicts the location of the study area and the placement of the NFP. (**a**) shows the location of Suqian, Jiangsu Province, China; The red area indicates the location of Santai Mountain NFP. (**b**) indicates the specific location of Santai Mountain NFP in Suqian; and (**c**) focuses on Santai Mountain NFP. Source: Background map shows national boundaries as defined by China's Department of Natural Resources. Base map of Suqian City from Jiangsu Provincial Department of Natural Resources Suqian City Political Area Map. Visit http://www.bigemap.com, accessed on 6 March 2023, for more information based on open-source data from BIGEMAP.



(**a**)



(**b**)

Figure 2. *Cont*.



(**c**)



(**d**)

Figure 2. The depictions of the Santai Mountain NFP in Jiangsu: (**a**) Flowers; (**b**) Woods; (**c**) Landscape Corridors; and (**d**) Water Features.



(**a**)



(**b**)



(**c**)



(**d**)



(**e**)



(**f**)

Figure 3. *Cont*.

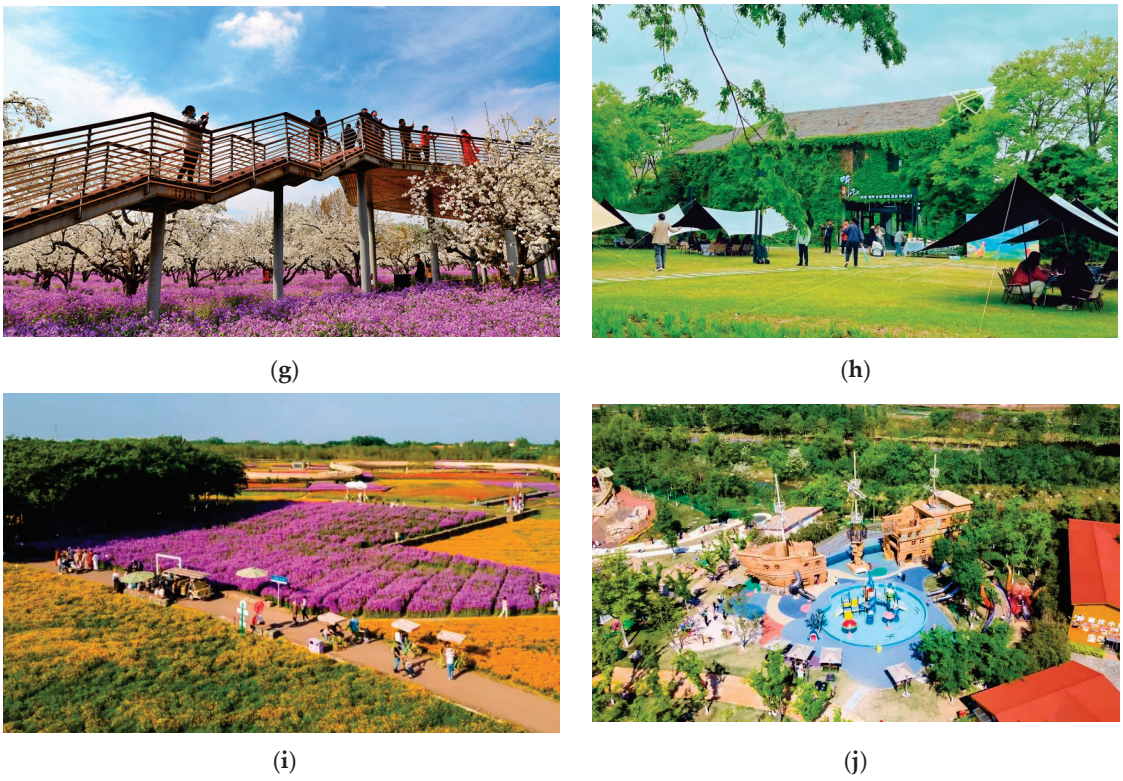


Figure 3. User activities in the Santai Mountain NFP, Jiangsu: (**a**) cycling; (**b**) flower-viewing; (**c**) walking; (**d**) music appreciation; (**e**) fishing; (**f**) watching a performance; (**g**) viewing platform; (**h**) camping; (**i**) agricultural sales; (**j**) children's playground.

2.2. The Conceptual Framework

Inspired by the work of Giles-Corti et al. (2005) [16] and Forsyth and Musacchio (2005) [26], a specific socio-ecological framework was developed for this study as a general conceptual model (refer to Figure 4). This framework adopts a socio-ecological approach and integrates the various multidisciplinary aspects of the issue under several key headings, aiming to understand how personal, environmental, and social attributes, as well as their interactions, influence the usage and safety perception experiences of national forest parks in urban green spaces.

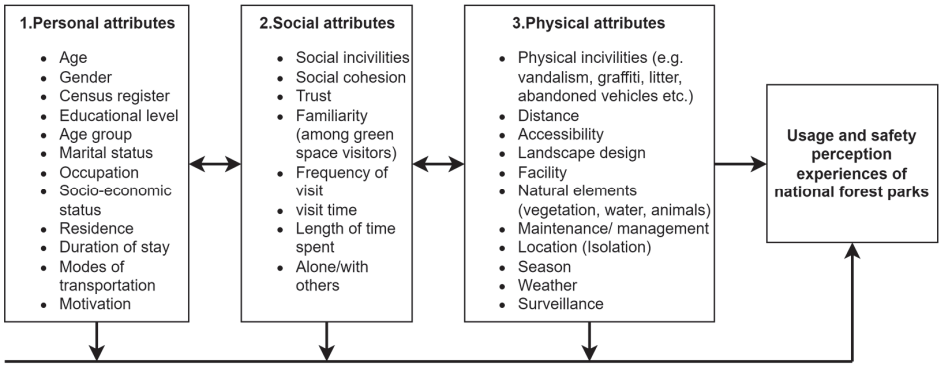


Figure 4. A conceptual framework for analyzing the usage and safety perception experiences of national forest parks based on a socio-ecological approach.

2.3. Survey Instruments and Procedure

The survey employed a semi-structured questionnaire to collect data, including pre-defined standard answers and open-ended questions. The participants were residents

and visitors who voluntarily took part in the overall utilization and safety assessment of Jiangsu Santai Mountain NFP. Since the study site and survey participants are in China, the questionnaire was administered in Chinese. This study confirms that all subjects provided informed consent. According to the methods outlined by Scheaffer et al. (2011) [27], convenience sampling was used to distribute the questionnaires throughout the park. To ensure effective data collection, surveyors first observed visitor flow in different areas of the forest park before starting the survey. Based on these observations, specific locations and time periods for on-site surveys were determined.

The on-site surveys focused on ten areas of the Santai Mountain NFP with high user activity and rest. Six surveyors assisted in conducting the surveys. Random sampling was employed to obtain a representative sample of NFP users, including adult users aged 18 and above. We conducted a pilot test with 30 visitors to eliminate any inappropriate wording. The survey was conducted from 28 March 2023 to 6 June 2024. The questionnaire combined on-site and online surveys. The survey was conducted through the "Wenjuanxing" online platform, which can generate QR codes and web links. Respondents could complete the on-site survey by scanning the QR code or filling out paper questionnaires, and they could also fill out the questionnaire online. This platform has a large population database and functions similarly to Amazon's Mechanical Turk. Since our respondents were Chinese residents, the questionnaire was presented in Mandarin. Respondents answered by scanning the QR code on the surveyor's iPad or mobile phone.

The on-site survey was conducted during residents' leisure times: weekdays in the mornings (7:00–10:00), afternoons (12:00–15:00), and evenings (16:00–18:00), as well as all day on weekends (7:00–18:00). Based on the ecological psychology conceptual model [28], the questionnaire was divided into three parts: the first part involved demographic information of the respondents (including gender, household registration, education level, age, income, occupation, and marital status). In quantitative analysis, demographic questions help understand the personal attributes of respondents and their impact on visitor usability and safety. The second part focused on visitors' usage patterns of the NFP (including visit frequency, time, distance, reasons for visiting, time spent, and companions). In the third part, a 4-point Likert scale was used to assess visitors' perceptions of safety for data analysis purposes. As a token of appreciation, respondents who completed the questionnaire received a souvenir worth 2 yuan.

2.4. Data Analysis

The statistical software SPSS, version 26.0, was used for data analysis, with the confidence level set at 95%. The survey was conducted in three phases. The first phase involved a descriptive quantitative analysis of the respondents' demographic information. In the second phase, descriptive statistics and chi-square tests were used to explore potential relationships between NFP usage patterns and sociodemographic variables. The chi-square test is a non-parametric test that primarily compares the association between two or more categorical variables [29]. In this study, the chi-square test was used to calculate the chi-square value (x^2) and the corresponding *p*-value. The *p*-value indicates the probability that the observed differences between samples are due to sampling error. A larger chi-square value corresponds to a smaller *p*-value, indicating a significant difference between the samples [30]. Conversely, a smaller chi-square value corresponds to a larger *p*-value, indicating no significant difference between the samples.

In the third phase, an ordinal logistic regression model was used to examine the safety of NFP usage. Safety levels were measured using a 4-point Likert scale (1—very safe, 2—safe, 3—not very safe, 4—very unsafe). Since the responses are discrete and ordered variables, they do not meet the assumptions of general linear regression. Ordinal regression is suitable for analyzing dependent variables with ordinal responses [29]. Therefore, we employed an ordinal logistic regression model.

3. Results

3.1. Visitor Usage Patterns

3.1.1. Demographic Features

Social factors play a pivotal role in shaping visitors' perceptions and experiences in national forest parks. These factors encompass a range of elements, including demographic characteristics, cultural background, social interactions, and previous experiences.

A total of 850 questionnaires were distributed, with 729 completed, resulting in an effective return rate of 85.76%. After excluding 41 invalid questionnaires, the final count of valid questionnaires was 688 (refer to Table 1). The statistical results indicate that males constitute 46.80% of the sample, while females make up 53.20%, showing a relatively even gender distribution. In terms of age, individuals aged 18–30 represent 35.47%, those aged 31–45 account for 54.80%, individuals aged 46–55 comprise 6.40%, those aged 56–65 constitute 2.33%, and individuals over 65 years old make up 1.02%. Regarding residency status, 78.20% have local household registration, while 21.80% are registered in other provinces and cities. Educational attainment reveals that 0.44% have an elementary education or below, 2.91% have a middle school education, 8.72% have a high school education, 73.11% have a college education, and 14.83% have a graduate education. This distribution is related to the improvement in the educational level in recent years in China. From the perspective of population structure, the respondents are predominantly young and middle-aged, a result of the continually improving education system in the country, leading to a high proportion of respondents with higher education levels. Regarding marital status, married individuals (64.68%) are approximately twice the number of unmarried individuals (33.72%). The occupations of residents are diverse, including employees of private enterprises (28.40%), government employees (36.09%), self-employed individuals (19.23%), unemployed individuals (7.10%), and students (7.69%). Monthly income distribution shows that 17.16% earn less than 3000 Yuan, 32.25% earn between 3001 and 6000 Yuan, 30.47% earn between 6001 and 10,000 Yuan, and 20.12% earn more than 10,000 Yuan.

Table 1. Sociodemographic characteristics of respondents (descriptive analysis).

Respondents		Number (n)	Percent (%)
1. Gender	Male	322	46.80
	Female	366	53.20
2.Census register	Local household registration	538	78.20
	Non-local household registration	150	21.80
3.Educational level	Primary school and below	3	0.44
	Junior high school	20	2.91
	High school/secondary	60	8.72
	University	503	73.11
	Postgraduate	102	14.83
4.Age group	18–30	244	35.47
	31–45	377	54.80
	46–55	44	6.40
	56–65	16	2.33
	>65	7	1.02
5.Marital status	Single	232	33.72
	Married	445	64.68
	Divorced	11	1.60
6.Occupation	Students	26	7.69
	Public sector	122	36.09
	Private employee	96	28.40
	Self-employed	65	19.23
	Pensioner	2	0.59
	Unemployed	24	7.10
7.Monthly income	<3000 Yuan	58	17.16
	3001–6000 Yuan	109	32.25
	6001–10,000 Yuan	103	30.47
	>10,000 Yuan	68	20.12

3.1.2. Visitor Patterns and Preferences in National Forest Parks

The analysis of visitor usage patterns in the National Forest Parks reveals a variety of behaviors and preferences that provide insights into how these natural spaces are utilized by the public. The data, summarized in Table 2, offers a detailed overview of the frequency of visits, preferred visiting times, and other relevant patterns.

Table 2. Analysis of forest park usage patterns (descriptive analysis).

Usability Pattern	Frequency (n)	Percentage (%)
Frequency of urban forest park visits		
1–2 times/year	439	63.81
1–2 times/month	142	20.64
1–2 times/week	45	6.54
3–4 times/week	26	3.78
Never	36	5.23
When do you prefer to come to this forest park?		
Weekdays	41	5.96
Weekends	171	24.85
Holidays	243	35.32
Special events	51	7.41
During spare time	182	26.45
What time of the day do you prefer to visit this forest park?		
Morning	303	44.04
Afternoon	264	38.37
Evening	101	14.68
Night	20	2.91
Length of time spent		
<1 h	62	9.01
1–2 h	265	38.52
2–3 h	241	35.03
3–4 h	85	12.35
>4 h	35	5.09
Mode of transportation		
on Foot	81	11.77
Bicycle	38	5.52
Electric bikes	57	8.28
Motorcycle	2	0.29
Car	453	65.84
Public transport	46	6.69
Others	11	1.60
Travel time		
<10 min	41	5.96
10–30 min	356	51.74
30–60 min	215	31.25
>1 h	76	11.05
How far have you traveled to get here?		
<1 km	28	4.07
1 km–2 km	48	6.98
2 km–5 km	102	14.83
5 km–10 km	305	44.33
>10 km	205	29.80
Visit with whom?		
Alone	46	6.69
With family	445	64.68
With friends	181	26.31
With dog	7	1.02
Others	9	1.31

The analysis of visitor usage patterns in National Forest Parks reveals diverse behaviors and preferences. Most visitors (63.81%) frequent the parks only 1–2 times per year, with fewer visiting monthly (20.64%) or weekly (10.32%). Holidays are the most popular visiting days (35.32%), followed by spare time (26.45%) and weekends (24.85%), while mornings are preferred by 44.04% of visitors, and afternoons by 38.37%. Visitors typically stay for 1–2 h (38.52%) or 2–3 h (35.03%), with shorter and longer visits being less common. The majority drive to the park (65.84%), with fewer arriving on foot (11.77%) or by bicycle (5.52%). Travel time varies, with 51.74% taking 10–30 min and 31.25% taking 30–60 min to reach the park. Distances traveled also differ, with 44.33% traveling 5–10 km and 29.80% more than 10 km. Most visitors come with family (64.68%), while others visit with friends (26.31%) or alone (6.69%). These findings highlight the need to accommodate diverse visitor needs to enhance overall park experiences. The results of the data analysis, as summarized in Table 3, primarily examine the user behavior patterns of respondents at NFP.

Table 3. User pattern by respondents at NFP (chi-square and Fisher's exact test measure x^2 and *p*-value).

	1. Frequency of the Forest Park Visit (%)				
	1–2 Times/Year	**1–2 Times/Month**	**1–2 Times/Week**	**3–4 Times/Week**	**Never**
1. Gender					
Male	210(47.84)	66(46.48)	18(40.00)	13(50.00)	15(41.67)
Female	229(52.16)	76(53.52)	27(60.00)	13(50.00)	21(58.33)
Pearson's χ^2 (*p*)	1.519(0.823)				
	0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 12.17.				
2. Census register					
Local household registration	347(79.04)	119(83.80)	28(62.22)	16(61.54)	28(77.78)
Non-local household Registration	92(20.96)	23(16.20)	17(37.78)	10(38.46)	8(22.22)
Pearson's χ^2 (*p*)	13.773(0.008 **)				
	0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 5.67.				
3. Educational level					
Primary school and below	0(0.00)	3(2.11)	0(0.00)	0(0.00)	0(0.00)
Junior high school	10(2.28)	3(2.11)	3(6.67)	1(3.85)	3(8.33)
High school/secondary	38(8.66)	11(7.75)	4(8.89)	0(0.00)	7(19.44)
University	323(73.58)	104(73.24)	31(68.89)	22(84.62)	23(63.89)
Postgraduate	68(15.49)	21(14.79)	7(15.56)	3(11.54)	3(8.33)
Pearson's χ^2 (*p*)	27.9(0.033 *)				
	13 cells (52.0%) have an expected count of less than 5. The minimum expected count is 0.11.				
4. Age group					
18–30 (years old)	146(33.26)	63(44.37)	18(40.00)	5(19.23)	12(33.33)
31–45 (years old)	248(56.49)	70(49.30)	22(48.89)	19(73.08)	18(50.00)
46–55 (years old)	32(7.29)	7(4.93)	3(6.67)	2(7.69)	0(0.00)
56–65 (years old)	9(2.05)	2(1.41)	2(4.44)	0(0.00)	3(8.33)
>65 (years old)	4(0.91)	0(0.00)	0(0.00)	0(0.00)	3(8.33)
Pearson's χ^2 (*p*)	41.325(0.000 ***)				
	12 cells (48.0%) have an expected count of less than 5. The minimum expected count is 0.26.				
5. Marital status					
Single	150(34.17)	44(30.99)	18(40.00)	3(11.54)	17(47.22)
Married	285(64.92)	94(66.20)	24(53.33)	23(88.46)	19(52.78)
Divorced	4(0.91)	4(2.82)	3(6.67)	0(0.00)	0(0.00)
Pearson's χ^2 (*p*)	21.455(0.006 **)				
	4 cells (26.7%) have an expected count of less than 5. The minimum expected count is 0.42.				
6. Occupation					
Students	29(6.61)	12(8.45)	6(13.33)	0(0.00)	8(22.22)
Public sector	154(35.08)	14(9.86)	5(11.11)	6(23.08)	1(2.78)
Private employee	139(31.66)	67(47.18)	11(24.44)	10(38.46)	14(38.89)
Self-employed	56(12.76)	25(17.61)	14(31.11)	0(0.00)	3(8.33)
Pensioner	13(2.96)	2(1.41)	4(8.89)	0(0.00)	3(8.33)
Unemployed	15(3.42)	2(1.41)	0(0.00)	1(3.85)	7(19.44)
Others	33(7.52)	20(14.08)	5(11.11)	9(34.62)	0(0.00)
Pearson's χ^2 (*p*)	140.998(0.000 ***)				
	14 cells (40.0%) have an expected count of less than 5. The minimum expected count is 0.83.				
7. Monthly income					
<3000 (yuan, RMB)	82(18.68)	15(10.56)	10(22.22)	2(7.69)	13(36.11)
3001–6000 (yuan, RMB)	133(30.30)	52(36.62)	17(37.78)	7(26.92)	14(38.89)
6001–10,000 (yuan, RMB)	135(30.75)	46(32.39)	5(11.11)	12(46.15)	2(5.56)
>10,000 (yuan, RMB)	89(20.27)	29(20.42)	13(28.89)	5(19.23)	7(19.44)
Pearson's χ^2 (*p*)	32.639(0.001 ***)				
	1 cell (5.0%) has an expected count of less than 5. The minimum expected count is 4.61.				

	2. When do you prefer to come to the forest park? (%)				
	Weekdays	Weekends	Holidays	Special events	During spare time
1. Gender					
Male	21(51.22)	80(46.78)	109(44.86)	21(41.18)	91(50.00)
Female	20(48.78)	91(53.22)	134(55.14)	30(58.82)	91(50.00)
Pearson's χ^2 (*p*)	2.087(0.72)				
	0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 19.19.				

Table 3. *Cont.*

	1. Frequency of the Forest Park Visit (%)				
	1–2 Times/Year	**1–2 Times/Month**	**1–2 Times/Week**	**3–4 Times/Week**	**Never**
2. Census register					
Local household registration	32(78.05)	121(70.76)	192(79.01)	41(80.39)	152(83.52)
Non-local household Registration	9(21.95)	50(29.24)	51(20.99)	10(19.61)	30(16.48)
Pearson's χ^2 (p)	8.807(0.066)				
0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 8.94.					
3. Educational level					
Primary school and below	3(7.32)	0(0.00)	0(0.00)	0(0.00)	0(0.00)
Junior high school	2(4.88)	4(2.34)	6(2.47)	2(3.92)	6(3.30)
High school/secondary	4(9.76)	10(5.85)	19(7.82)	2(3.92)	25(13.74)
University	22(53.66)	130(76.02)	181(74.49)	46(90.20)	124(68.13)
Postgraduate	0(0.00)	6(3.3)	25(13.7)	124(68.1)	27(14.8)
Pearson's χ^2 (p)	70.4(0.000 ***)				
10 cells (40.0%) have an expected count of less than 5. The minimum expected count is 0.18.					
4. Age group					
18–30 (years old)	16(39.02)	58(33.92)	80(32.92)	26(50.98)	64(35.16)
31–45 (years old)	18(43.90)	108(63.16)	139(57.20)	20(39.22)	92(50.55)
46–55 (years old)	3(7.32)	5(2.92)	19(7.82)	3(5.88)	14(7.69)
56–65 (years old)	0(0.00)	0(0.00)	5(2.06)	2(3.92)	9(4.95)
>65 (years old)	4(9.76)	0(0.00)	0(0.00)	0(0.00)	3(1.65)
Pearson's χ^2 (p)	62.052(0.000 ***)				
11 cells (44.0%) have an expected count of less than 5. The minimum expected count is 0.42.					
5. Marital status					
Single	21(51.22)	53(30.99)	80(32.92)	23(45.10)	55(30.22)
Married	19(46.34)	115(67.25)	156(64.20)	28(54.90)	127(69.78)
Divorced	1(2.44)	3(1.75)	7(2.88)	0(0.00)	0(0.00)
Pearson's χ^2 (p)	16.996(0.030 *)				
5 cells (33.3%) have an expected count of less than 5. The minimum expected count is 0.66.					
6. Occupation					
Students	11(26.83)	8(4.68)	17(7.00)	2(3.92)	17(9.34)
Public sector	8(19.51)	47(27.49)	88(36.21)	12(23.53)	25(13.74)
Private employee	7(17.07)	81(47.37)	68(27.98)	22(43.14)	63(34.62)
Self-employed	10(24.39)	18(10.53)	32(13.17)	11(21.57)	27(14.84)
Pensioner	0(0.00)	0(0.00)	7(2.88)	2(3.92)	13(7.14)
Unemployed	2(4.88)	3(1.75)	5(2.06)	1(1.96)	14(7.69)
others	3(7.32)	14(8.19)	26(10.70)	1(1.96)	23(12.64)
Pearson's χ^2 (p)	99.367(0.000 ***)				
8 cells (22.9%) have an expected count of less than 5. The minimum expected count is 1.31.					
7. Monthly income					
<3000 (yuan, RMB)	17(41.46)	15(8.77)	45(18.52)	9(17.65)	36(19.78)
3001–6000 (yuan, RMB)	6(14.63)	72(42.11)	73(30.04)	22(43.14)	50(27.47)
6001–10,000 (yuan, RMB)	11(26.83)	58(33.92)	80(32.92)	5(9.80)	46(25.27)
>10,000 (yuan, RMB)	7(17.07)	26(15.20)	45(18.52)	15(29.41)	50(27.47)
Pearson's χ^2 (p)	53.119(0.000 ***)				
0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 7.27.					

	3. What time of the day do you prefer to visit the forest Park?(%)			
	Morning	Afternoon	Evening	Night
1. Gender				
Male	144(47.52)	127(48.11)	38(37.62)	13(65.00)
Female	159(52.48)	137(51.89)	63(62.38)	7(35.00)
Pearson's χ^2 (p)	6.321(0.097)			
0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 9.36.				
2. Census register				
Local household registration	250(82.51)	202(76.52)	71(70.30)	15(75.00)
Non-local household Registration	53(17.49)	62(23.48)	30(29.70)	5(25.00)
Pearson's χ^2 (p)	7.558(0.056)			
1 cell (12.5%) has an expected count of less than 5. The minimum expected count is 4.36.				
3. Educational level				
Primary school and below	3(0.99)	0(0.00)	0(0.00)	0(0.00)
Junior high school	8(2.64)	6(2.27)	4(3.96)	2(10.00)
High school/secondary	19(6.27)	18(6.82)	18(17.82)	5(25.00)
University	213(70.30)	219(82.95)	62(61.39)	9(45.00)
Postgraduate	60(19.80)	21(7.95)	17(16.83)	4(20.00)
Pearson's χ^2 (p)	48.942(0.000 ***)			
8 cells (40.0%) have an expected count of less than 5. The minimum expected count is 0.09.				
4. Age group				
18–30 (years old)	77(25.41)	124(46.97)	35(34.65)	8(40.00)
31–45 (years old)	190(62.71)	122(46.21)	56(55.45)	9(45.00)
46–55 (years old)	18(5.94)	16(6.06)	10(9.90)	0(0.00)
56–65 (years old)	14(4.62)	2(0.76)	0(0.00)	0(0.00)
>65 (years old)	4(1.32)	0(0.00)	0(0.00)	3(15.00)
Pearson's χ^2 (p)	84.238(0.000 ***)			
7 cells (35.0%) have an expected count of less than 5. The minimum expected count is 0.20.				
5. Marital status				
Single	66(21.78)	122(46.21)	34(33.66)	10(50.00)
Married	232(76.57)	139(52.65)	64(63.37)	10(50.00)
Divorced	5(1.65)	3(1.14)	3(2.97)	0(0.00)
Pearson's χ^2 (p)	41.68(0.000 ***)			
4 cells (33.3%) have an expected count of less than 5. The minimum expected count is 0.32.				

Table 3. *Cont.*

	1. Frequency of the Forest Park Visit (%)				
	1–2 Times/Year	**1–2 Times/Month**	**1–2 Times/Week**	**3–4 Times/Week**	**Never**
6. Occupation					
Students	21(6.93)	21(7.95)	7(6.93)	6(30.00)	
Public sector	79(26.07)	61(23.11)	32(31.68)	8(40.00)	
Private employee	101(33.33)	105(39.77)	34(33.66)	1(5.00)	
Self-employed	45(14.85)	34(12.88)	17(16.83)	2(10.00)	
Pensioner	14(4.62)	4(1.52)	4(3.96)	0(0.00)	
Unemployed	9(2.97)	12(4.55)	1(0.99)	3(15.00)	
others	34(11.22)	27(10.23)	6(5.94)	0(0.00)	
Pearson's χ^2 (p)	43.865(0.001 ***)				
	7 cells (25.0%) have an expected count of less than 5. The minimum expected count is 0.64.				
7. Monthly income					
<3000 (yuan, RMB)	45(14.85)	48(18.18)	19(18.81)	10(50.00)	
3001–6000 (yuan, RMB)	82(27.06)	97(36.74)	39(38.61)	5(25.00)	
6001–10,000 (yuan, RMB)	110(36.30)	59(22.35)	31(30.69)	0(0.00)	
>10,000 (yuan, RMB)	66(21.78)	60(22.73)	12(11.88)	5(25.00)	
Pearson's χ^2 (p)	39.108(0.000 ***)				
	2 cells (12.5%) have an expected count of less than 5. The minimum expected count is 3.55.				

	4. Length of time spent (%)				
	<1 h	1–2 h	2–3 h	3–4 h	>4 h
1. Gender					
Male	26(41.94)	127(47.92)	109(45.23)	40(47.06)	20(57.14)
Female	36(58.06)	138(52.08)	132(54.77)	45(52.94)	15(42.86)
Pearson's χ^2 (p)	2.469(0.65)				
	0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 16.38.				
2. Census register					
Local household registration	45(72.58)	205(77.36)	185(76.76)	70(82.35)	33(94.29)
Non-local household Registration	17(27.42)	60(22.64)	56(23.24)	15(17.65)	2(5.71)
Pearson's χ^2 (p)	7.722(0.102)				
	0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 7.63.				
3. Educational level					
Primary school and below	3(4.84)	0(0.00)	0(0.00)	0(0.00)	0(0.00)
Junior high school	7(11.29)	6(2.26)	5(2.07)	2(2.35)	0(0.00)
High school/secondary	9(14.52)	29(10.94)	19(7.88)	0(0.00)	3(8.57)
University	35(56.45)	203(76.60)	174(72.20)	67(78.82)	24(68.57)
Postgraduate	8(12.90)	27(10.19)	43(17.84)	16(18.82)	8(22.86)
Pearson's χ^2 (p)	70.051(0.000 ***)				
	9 cells (36.0%) have an expected count of less than 5. The minimum expected count is 0.15.				
4. Age group					
18–30 (years old)	27(43.55)	117(44.15)	74(30.71)	19(22.35)	7(20.00)
31–45 (years old)	31(50.00)	127(47.92)	138(57.26)	56(65.88)	25(71.43)
46–55 (years old)	0(0.00)	15(5.66)	22(9.13)	7(8.24)	0(0.00)
56–65 (years old)	0(0.00)	6(2.26)	7(2.90)	3(3.53)	0(0.00)
>65 (years old)	4(6.45)	0(0.00)	0(0.00)	0(0.00)	3(8.57)
Pearson's χ^2 (p)	77.752(0.000 ***)				
	10 cells (40.0%) have an expected count of less than 5. The minimum expected count is 0.36.				
5. Marital status					
Single	32(51.61)	96(36.23)	74(30.71)	20(23.53)	10(28.57)
Married	30(48.39)	166(62.64)	162(67.22)	65(76.47)	22(62.86)
Divorced	0(0.00)	3(1.13)	5(2.07)	0(0.00)	3(8.57)
Pearson's χ^2 (p)	28.418(0.000 ***)				
	5 cells (33.3%) have an expected count of less than 5. The minimum expected count is 0.56.				
6. Occupation					
Students	7(11.29)	18(6.79)	13(5.39)	14(16.47)	3(8.57)
Public sector	17(27.42)	72(27.17)	68(28.22)	16(18.82)	7(20.00)
Private employee	26(41.94)	95(35.85)	89(36.93)	27(31.76)	4(11.43)
Self-employed	3(4.84)	36(13.58)	33(13.69)	15(17.65)	11(31.43)
Pensioner	2(3.23)	4(1.51)	7(2.90)	6(7.06)	3(8.57)
Unemployed	7(11.29)	9(3.40)	6(2.49)	1(1.18)	2(5.71)
others	0(0.00)	31(11.70)	25(10.37)	6(7.06)	5(14.29)
Pearson's χ^2 (p)	63.541(0.000 ***)				
	10 cells (28.6%) have an expected count of less than 5. The minimum expected count is 1.12.				
7. Monthly income					
<3000 (yuan, RMB)	25(40.32)	41(15.47)	36(14.94)	20(23.53)	0(0.00)
3001–6000 (yuan, RMB)	19(30.65)	108(40.75)	66(27.39)	21(24.71)	9(25.71)
6001–10,000 (yuan, RMB)	11(17.74)	70(26.42)	90(37.34)	23(27.06)	6(17.14)
>10,000 (yuan, RMB)	7(11.29)	46(17.36)	49(20.33)	21(24.71)	20(57.14)
Pearson's χ^2 (p)	75.14(0.000 ***)				
	0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 6.21.				

	5. Mode of transportation (%)						
	on Foot	Bicycle	Electric bikes	Motorcycle	Car	Public transport	Others
1. Gender							
Male	47(58.02)	26(68.42)	20(35.09)	1(50.00)	208(45.92)	16(34.78)	4(36.36)
Female	34(41.98)	12(31.58)	37(64.91)	1(50.00)	245(54.08)	30(65.22)	7(63.64)
Pearson's χ^2 (p)	17.674(0.007 **)						
	2 cells (14.3%) have an expected count of less than 5. The minimum expected count is 0.94.						
2. Census register							
Local household registration	53(65.43)	26(68.42)	26(45.61)	2(100.00)	393(86.75)	30(65.22)	8(72.73)
Non-local household Registration	28(34.57)	12(31.58)	31(54.39)	0(0.00)	60(13.25)	16(34.78)	3(27.27)
Pearson's χ^2 (p)	70.122(0.000 ***)						
	3 cells (21.4%) have an expected count of less than 5. The minimum expected count is 0.44.						

Table 3. *Cont.*

	1. Frequency of the Forest Park Visit (%)						
	1–2 Times/Year		**1–2 Times/Month**	**1–2 Times/Week**		**3–4 Times/Week**	**Never**
3. Educational level							
Primary school and below	0(0.00)	3(7.89)	0(0.00)	0(0.00)	0(0.00)	0(0.00)	0(0.00)
Junior high school	1(1.23)	2(5.26)	3(5.26)	1(50.00)	12(2.65)	1(2.17)	0(0.00)
High school/secondary	6(7.41)	2(5.26)	5(8.77)	1(50.00)	37(8.17)	4(8.70)	5(45.45)
University	56(69.14)	26(68.42)	29(50.88)	0(0.00)	357(78.81)	32(69.57)	3(27.27)
Postgraduate	18(22.22)	5(13.16)	20(35.09)	0(0.00)	47(10.38)	9(19.57)	3(27.27)
Pearson's χ^2 (p)	129.341(0.000 ***)						
	21 cells (60.0%) have an expected count of less than 5. The minimum expected count is 0.01.						
4. Age group							
18–30 (years old)	37(45.68)	24(63.16)	33(57.89)	0(0.00)	121(26.71)	27(58.70)	2(18.18)
31–45 (years old)	38(46.91)	12(31.58)	22(38.60)	0(0.00)	283(62.47)	16(34.78)	6(54.55)
46–55 (years old)	2(2.47)	0(0.00)	2(3.51)	2(100.00)	38(8.39)	0(0.00)	0(0.00)
56–65 (years old)	0(0.00)	2(5.26)	0(0.00)	0(0.00)	11(2.43)	3(6.52)	0(0.00)
>65 (years old)	4(4.94)	0(0.00)	0(0.00)	0(0.00)	0(0.00)	0(0.00)	3(27.27)
Pearson's χ^2 (p)	194.066(0.000 ***)						
	21 cells (60.0%) have an expected count of less than 5. The minimum expected count is 0.02.						
5. Marital status							
Single	46(56.79)	20(52.63)	39(68.42)	0(0.00)	85(18.76)	37(80.43)	5(45.45)
Married	35(43.21)	16(42.11)	18(31.58)	1(50.00)	361(79.69)	8(17.39)	6(54.55)
Divorced	0(0.00)	2(5.26)	0(0.00)	1(50.00)	7(1.55)	1(2.17)	0(0.00)
Pearson's χ^2 (p)	183.442(0.000 ***)						
	9 cells (42.9%) have an expected count of less than 5. The minimum expected count is 0.03.						
6. Occupation							
Students	15(18.52)	6(15.79)	13(22.81)	0(0.00)	14(3.09)	4(8.70)	3(27.27)
Public sector	27(33.33)	8(21.05)	15(26.32)	0(0.00)	125(27.59)	5(10.87)	0(0.00)
Private employee	25(30.86)	16(42.11)	16(28.07)	2(100.00)	156(34.44)	23(50.00)	3(27.27)
Self-employed	8(9.88)	5(13.16)	7(12.28)	0(0.00)	74(16.34)	4(8.70)	0(0.00)
Pensioner	0(0.00)	0(0.00)	0(0.00)	0(0.00)	18(3.97)	4(8.70)	0(0.00)
Unemployed	3(3.70)	0(0.00)	2(3.51)	0(0.00)	11(2.43)	6(13.04)	3(27.27)
others	3(3.70)	3(7.89)	4(7.02)	0(0.00)	55(12.14)	0(0.00)	2(18.18)
Pearson's χ^2 (p)	125.75(0.000 ***)						
	27 cells (55.1%) have an expected count of less than 5. The minimum expected count is 0.06.						
7. Monthly income							
<3000 (yuan, RMB)	15(18.52)	12(31.58)	21(36.84)	0(0.00)	51(11.26)	18(39.13)	5(45.45)
3001–6000 (yuan, RMB)	29(35.80)	14(36.84)	25(43.86)	1(50.00)	141(31.13)	13(28.26)	0(0.00)
6001–10,000 (yuan, RMB)	23(28.40)	4(10.53)	10(17.54)	1(50.00)	150(33.11)	11(23.91)	1(9.09)
>10,000 (yuan, RMB)	14(17.28)	8(21.05)	1(1.75)	0(0.00)	111(24.50)	4(8.70)	5(45.45)
Pearson's χ^2 (p)	82.824(0.000 ***)						
	8 cells (28.6%) have an expected count of less than 5. The minimum expected count is 0.35.						

	6. Travel time from home to destination (%)			
	<10 min	**10–30 min**	**30–60 min**	**>1 h**
1. Gender				
Male	22(53.66)	170(47.75)	95(44.19)	35(46.05)
Female	19(46.34)	186(52.25)	120(55.81)	41(53.95)
Pearson's χ^2 (p)	1.512(0.68)			
	0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 19.19.			
2. Census register				
Local household registration	35(85.37)	291(81.74)	177(82.33)	35(46.05)
Non-local household Registration	6(14.63)	65(18.26)	38(17.67)	41(53.95)
Pearson's χ^2 (p)	52.069(0.000 ***)			
	0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 8.94.			
3. Educational level				
Primary school and below	3(7.32)	0(0.00)	0(0.00)	0(0.00)
Junior high school	3(7.32)	3(0.84)	13(6.05)	1(1.32)
High school/secondary	7(17.07)	37(10.39)	11(5.12)	5(6.58)
University	21(51.22)	276(77.53)	162(75.35)	44(57.89)
Postgraduate	7(17.07)	40(11.24)	29(13.49)	26(34.21)
Pearson's χ^2 (p)	100.228(0.000 ***)			
	7 cells (35.0%) have an expected count of less than 5. The minimum expected count is 0.18.			
4. Age group				
18–30 (years old)	17(41.46)	106(29.78)	84(39.07)	37(48.68)
31–45 (years old)	20(48.78)	220(61.80)	106(49.30)	31(40.79)
46–55 (years old)	0(0.00)	22(6.18)	17(7.91)	5(6.58)
56–65 (years old)	0(0.00)	8(2.25)	8(3.72)	0(0.00)
>65 (years old)	4(9.76)	0(0.00)	0(0.00)	3(3.95)
Pearson's χ^2 (p)	66.504(0.000 ***)			
	8 cells (40.0%) have an expected count of less than 5. The minimum expected count is 0.42.			
5. Marital status				
Single	14(34.15)	103(28.93)	73(33.95)	42(55.26)
Married	27(65.85)	248(69.66)	138(64.19)	32(42.11)
Divorced	0(0.00)	5(1.40)	4(1.86)	2(2.63)
Pearson's χ^2 (p)	21.596(0.001 ***)			
	3 cells (25.0%) have an expected count of less than 5. The minimum expected count is 0.66.			
6. Occupation				
Students	9(21.95)	18(5.06)	12(5.58)	16(21.05)
Public sector	8(19.51)	92(25.84)	63(29.30)	17(22.37)
Private employee	18(43.90)	122(34.27)	82(38.14)	19(25.00)
Self-employed	3(7.32)	48(13.48)	32(14.88)	15(19.74)
Pensioner	2(4.88)	12(3.37)	7(3.26)	1(1.32)
Unemployed	1(2.44)	12(3.37)	6(2.79)	6(7.89)
others	0(0.00)	52(14.61)	13(6.05)	2(2.63)
Pearson's χ^2 (p)	65.795(0.000 ***)			
	6 cells (21.4%) have an expected count of less than 5. The minimum expected count is 1.31.			

Table 3. *Cont.*

	1. Frequency of the Forest Park Visit (%)				
	1–2 Times/Year	**1–2 Times/Month**	**1–2 Times/Week**	**3–4 Times/Week**	**Never**
7. Monthly income					
<3000 (yuan, RMB)	17(41.46)	37(10.39)	46(21.40)	22(28.95)	
3001–6000 (yuan, RMB)	15(36.59)	122(34.27)	69(32.09)	17(22.37)	
6001–10,000 (yuan, RMB)	8(19.51)	109(30.62)	63(29.30)	20(26.32)	
>10,000 (yuan, RMB)	1(2.44)	88(24.72)	37(17.21)	17(22.37)	
Pearson's χ^2 (p)	46.312(0.000 ***)				
0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 7.27.					
	7. How far have you traveled to get here? (%)				
	<1 km	1 km–2 km	2 km–5 km	5 km–10 km	>10 km
1. Gender					
Male	13(46.43)	32(66.67)	37(36.27)	145(47.54)	95(46.34)
Female	15(53.57)	16(33.33)	65(63.73)	160(52.46)	110(53.66)
Pearson's χ^2 (p)	1.509(0.813)				
0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 13.10.					
2. Census register					
Local household registration	21(75.00)	23(47.92)	76(74.51)	269(88.20)	149(72.68)
Non-local household Registration	7(25.00)	25(52.08)	26(25.49)	36(11.80)	56(27.32)
Pearson's χ^2 (p)	48.341(0.000 ***)				
0 cells (0.0%) have an expected count of less than 5. The minimum expected count is 6.10.					
3. Educational level					
Primary school and below	0(0.00)	3(6.25)	0(0.00)	0(0.00)	0(0.00)
Junior high school	5(17.86)	2(4.17)	1(0.98)	7(2.30)	5(2.44)
High school/secondary	4(14.29)	1(2.08)	8(7.84)	29(9.51)	18(8.78)
University	13(46.43)	35(72.92)	79(77.45)	225(73.77)	151(73.66)
Postgraduate	6(21.43)	7(14.58)	14(13.73)	44(14.43)	31(15.12)
Pearson's χ^2 (p)	71.337(0.000 ***)				
11 cells (44.0%) have an expected count of less than 5. The minimum expected count is 0.12.					
4. Age group					
18–30 (years old)	7(25.00)	29(60.42)	39(38.24)	96(31.48)	73(35.61)
31–45 (years old)	17(60.71)	19(39.58)	56(54.90)	174(57.05)	111(54.15)
46–55 (years old)	0(0.00)	0(0.00)	4(3.92)	25(8.20)	15(7.32)
56–65 (years old)	0(0.00)	0(0.00)	3(2.94)	10(3.28)	3(1.46)
>65 (years old)	4(14.29)	0(0.00)	0(0.00)	0(0.00)	3(1.46)
Pearson's χ^2 (p)	78.301(0.000 ***)				
11 cells (44.0%) have an expected count of less than 5. The minimum expected count is 0.28.					
5. Marital status					
Single	12(42.86)	25(52.08)	31(30.39)	85(27.87)	79(38.54)
Married	14(50.00)	22(45.83)	70(68.63)	213(69.84)	126(61.46)
Divorced	2(7.14)	1(2.08)	1(0.98)	7(2.30)	0(0.00)
Pearson's χ^2 (p)	25.631(0.001 ***)				
5 cells (33.3%) have an expected count of less than 5. The minimum expected count is 0.45.					
6. Occupation					
Students	6(21.43)	12(25.00)	11(10.78)	14(4.59)	12(5.85)
Public sector	8(28.57)	12(25.00)	24(23.53)	84(27.54)	52(25.37)
Private employee	11(39.29)	12(25.00)	39(38.24)	108(35.41)	71(34.63)
Self-employed	0(0.00)	11(22.92)	10(9.80)	45(14.75)	32(15.61)
Pensioner	0(0.00)	0(0.00)	0(0.00)	13(4.26)	9(4.39)
Unemployed	3(10.71)	1(2.08)	0(0.00)	6(1.97)	15(7.32)
Others	0(0.00)	0(0.00)	18(17.65)	35(11.48)	14(6.83)
Pearson's χ^2 (p)	83.242(0.000 ***)				
11 cells (31.4%) have an expected count of less than 5. The minimum expected count is 0.90.					
7. Monthly income					
<3000 (yuan, RMB)	10(35.71)	15(31.25)	15(14.71)	41(13.44)	41(20.00)
3001–6000 (yuan, RMB)	5(17.86)	21(43.75)	44(43.14)	98(32.13)	55(26.83)
6001–10,000 (yuan, RMB)	13(46.43)	4(8.33)	20(19.61)	104(34.10)	59(28.78)
>10,000 (yuan, RMB)	0(0.00)	8(16.67)	23(22.55)	62(20.33)	50(24.39)
Pearson's χ^2 (p)	47.15(0.000 ***)				
1 cell (5.0%) has an expected count of less than 5. The minimum expected count is 4.97.					
	8. Visit with whom? (%)				
	Alone	With family	With friends	With dog	Others
1. Gender					
Male	27(58.70)	186(41.80)	96(53.04)	7(100.00)	6(66.67)
Female	19(41.30)	259(58.20)	85(46.96)	0(0.00)	3(33.33)
Pearson's χ^2 (p)	19.3(0.001 ***)				
4 cells (40.0%) have an expected count of less than 5. The minimum expected count is 3.28.					
2. Census register					
Local household registration	31(67.39)	393(88.31)	102(56.35)	6(85.71)	6(66.67)
Non-local household Registration	15(32.61)	52(11.69)	79(43.65)	1(14.29)	3(33.33)
Pearson's χ^2 (p)	81.458(0.000 ***)				
2 cells (20.0%) have an expected count of less than 5. The minimum expected count is 1.53.					
3. Educational level					
Primary school and below	0(0.00)	3(0.67)	0(0.00)	0(0.00)	0(0.00)
Junior high school	0(0.00)	18(4.04)	2(1.10)	0(0.00)	0(0.00)
High school/secondary	7(15.22)	42(9.44)	6(3.31)	0(0.00)	5(55.56)
University	33(71.74)	320(71.91)	142(78.45)	4(57.14)	4(44.44)
Postgraduate	6(13.04)	62(13.93)	31(17.13)	3(42.86)	0(0.00)
Pearson's χ^2 (p)	47.337(0.000 ***)				
13 cells (52.0%) have an expected count of less than 5. The minimum expected count is 0.03.					

Table 3. *Cont.*

	1. Frequency of the Forest Park Visit (%)				
	1–2 Times/Year	**1–2 Times/Month**	**1–2 Times/Week**	**3–4 Times/Week**	**Never**
4. Age group					
18–30 (years old)	31(67.39)	97(21.80)	113(62.43)	1(14.29)	2(22.22)
31–45 (years old)	9(19.57)	296(66.52)	59(32.60)	6(85.71)	7(77.78)
46–55 (years old)	0(0.00)	37(8.31)	7(3.87)	0(0.00)	0(0.00)
56–65 (years old)	2(4.35)	12(2.70)	2(1.10)	0(0.00)	0(0.00)
>65 (years old)	4(8.70)	3(0.67)	0(0.00)	0(0.00)	0(0.00)
Pearson's χ^2 (p)	155.158(0.000 ***)				
	16 cells (64.0%) have an expected count of less than 5. The minimum expected count is 0.07.				
5. Marital status					
Single	40(86.96)	58(13.03)	133(73.48)	1(14.29)	0(0.00)
Married	6(13.04)	383(86.07)	41(22.65)	6(85.71)	9(100.00)
Divorced	0(0.00)	4(0.90)	7(3.87)	0(0.00)	0(0.00)
Pearson's χ^2 (p)	294.066(0.000 ***)				
	7 cells (46.7%) have an expected count of less than 5. The minimum expected count is 0.11.				
6. Occupation					
Students	7(15.22)	17(3.82)	31(17.13)	0(0.00)	0(0.00)
Public sector	14(30.43)	124(27.87)	34(18.78)	6(85.71)	2(22.22)
Private employee	23(50.00)	151(33.93)	62(34.25)	1(14.29)	4(44.44)
Self-employed	2(4.35)	67(15.06)	29(16.02)	0(0.00)	0(0.00)
Pensioner	0(0.00)	20(4.49)	2(1.10)	0(0.00)	0(0.00)
Unemployed	0(0.00)	10(2.25)	12(6.63)	0(0.00)	3(33.33)
Others	0(0.00)	56(12.58)	11(6.08)	0(0.00)	0(0.00)
Pearson's χ^2 (p)	106.88(0.000 ***)				
	18 cells (51.4%) have an expected count of less than 5. The minimum expected count is 0.22.				
7. Monthly income					
<3000 (yuan, RMB)	16(34.78)	47(10.56)	54(29.83)	0(0.00)	5(55.56)
3001–6000 (yuan, RMB)	18(39.13)	140(31.46)	64(35.36)	1(14.29)	0(0.00)
6001–10,000 (yuan, RMB)	9(19.57)	145(32.58)	43(23.76)	3(42.86)	0(0.00)
>10,000 (yuan, RMB)	3(6.52)	113(25.39)	20(11.05)	3(42.86)	4(44.44)
Pearson's χ^2 (p)	78.291(0.000 ***)				
	8 cells (40.0%) have an expected count of less than 5. The minimum expected count is 1.24.				

* $p \leq 0.05$ (significant), ** $p \leq 0.01$ (more significant), *** $p \leq 0.001$ (highly significant).

3.2. Perception of Forest Park Safety

The perception of safety within National Forest Parks reflects a generally positive outlook among visitors, as indicated by the data presented in Table 4. A majority of respondents, 52.76%, perceive the parks as "safe," while 36.92% consider them to be "very safe." Only a small minority of visitors express concerns about safety, with 6.10% indicating that they feel "not very safe," and an even smaller group, 0.87%, describing the parks as "very unsafe." These findings suggest that the vast majority of visitors feel secure when visiting these parks, which is crucial for encouraging continued public use and enjoyment of these natural spaces. The respondents' perception of safety when using the NFP was analyzed using an ordered logistic regression model to measure the odds ratio (OR) and *p*-value (refer to Table 5).

Table 4. Perception of safety in urban forest parks of Suqian (descriptive analysis).

Do You Think the Forest Park Is Safe?	Frequency (n)	Percent (%)
Very safe	254	36.92
Safe	363	52.76
Not very safe	42	6.10
Very Unsafe	6	0.87

Table 5. The respondents' Perception of safety in using the NFP (ordered logistic regression model measure the odd ratio (OR) and *p*-value).

	B	Std. Error	Sig.	Exp(B)(OR)	Lower	Upper
1. Gender						
Male	−0.254	0.1794	0.157	0.776	0.546	1.102
Female	0 [a]			1		
2. Census register						
Local household registration	−0.181	0.2201	0.412	0.835	0.542	1.285
Non-local household registration	0 [a]			1		

Table 5. *Cont.*

	B	Std. Error	Sig.	Exp(B)(OR)	Lower	Upper
3. Educational level						
Primary school and below	−2.407	1.1719	0.040 **	0.090	0.009	0.896
Junior high school	−0.187	0.5263	0.722	0.829	0.296	2.327
High school/secondary	0.094	0.3755	0.802	1.099	0.526	2.294
University	−0.434	0.2536	0.087 *	0.648	0.394	1.065
Postgraduate	0 [a]			1		
4. Age group						
18–30	3.303	0.8238	0.000 ***	27.201	5.412	136.720
31–45	3.616	0.8395	0.000 ***	37.175	7.172	192.679
46–55	4.016	0.9039	0.000 ***	55.472	9.434	326.173
56–65	5.238	0.9869	0.000 ***	188.270	27.208	1302.762
>65	0 [a]			1		
5. Marital status						
Single	1.725	0.7291	0.018 **	5.615	1.345	23.441
Married	1.115	0.6981	0.110	3.050	0.776	11.983
Divorced	0 [a]			1		
6. Occupation						
Students	0.361	0.4495	0.423	1.434	0.594	3.461
Public sector	−0.636	0.3042	0.037	0.530	0.292	0.961
Private employee	−0.831	0.2943	0.005 **	0.435	0.245	0.775
Self-employed	−0.482	0.3366	0.152	0.618	0.319	1.195
Pensioner	−0.513	0.4880	0.293	0.599	0.230	1.558
Unemployed	1.029	0.5189	0.047 **	2.798	1.012	7.737
Others	0 [a]			1		
7. Monthly income						
<3000 Yuan	−0.620	0.3407	0.069 *	0.538	0.276	1.049
3001–6000 Yuan	−0.161	0.2486	0.517	0.851	0.523	1.385
6001–10,000 Yuan	−0.579	0.2248	0.010 *	0.560	0.361	0.871
>10,000 Yuan	0 [a]			1		

0 [a], meaning it is the reference category. For example, gender: "Female" is marked as "0 [a]", meaning it is the reference category, and the results for "Male" are compared to "Female." 95% Wald Confidence Interval for Exp(B). * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

4. Discussion

4.1. Preferences for Usage Patterns of Forest Parks

Environmental factors are equally critical in determining the quality of visitor experiences and safety perceptions in national forest parks. These factors include the physical attributes of the park, maintenance, and the presence of facilities and amenities.

The usage patterns of NFPs are presented in Table 2. This study employs chi-square tests to compare the influence of demographic variables on preferences for usage patterns of forest parks (refer to Table 3). The majority of respondents in the study, comprising 63.81%, reported visiting the forest park only 1–2 times per year. This is hardly surprising given that 42.3% require driving more than 30 min to access the urban forest park. In China, many forest parks are far away from the city center. A study conducted in the United States found that when the distance between green spaces and residential areas is shortened by 100 m, the utilization rate of green spaces increases fourfold [31]; conversely, the utilization rate decreases as the distance increases. Therefore, we can hypothesize that the distance to NFPs plays a significant role in determining the frequency of their use. There are also statistically significant differences in terms of gender ($p < 0.01$), census register ($p < 0.01$), educational level ($p < 0.01$), age ($p < 0.01$), marital status ($p < 0.01$), occupation ($p < 0.01$), and monthly income ($p < 0.01$) (refer to Table 3).

The number of women visiting forest parks 1–2 times per month exceeds that of men, which contrasts with the research of Dai et al. [32]. Studies and surveys indicate that women need more time to care for and accompany their children, providing them with more opportunities to go out and enjoy nature. Simultaneously, we observe that

residents with a college education visit forest parks much more frequently than those without a college education. This suggests that residents with higher educational levels frequent forest parks more often than those with lower educational levels, likely because higher education provides greater opportunities for stable employment and income. In terms of marital status, married residents visit forest parks significantly more frequently than single residents. Notably, the number of married residents who visit 3–4 times per week is seven times higher than that of unmarried residents. This finding indicates that companionship may positively influence the frequency of outdoor activities [18,33,34]. Previous studies have confirmed that companionship positively impacts mental health and actively promotes outdoor activities [35–38]. There are also significant differences among various occupations: employees of private enterprises and public sector workers visit forest parks more frequently. This may be because employees in the private sector have more opportunities for outdoor activities and team-building events organized by their companies.

Surveys indicate that most tourists prefer to visit NFPs on weekends (24.85%), holidays (35.32%), and during their spare time (26.45%). Clearly, visitors enjoy spending their leisure time in nature [34,39–41]. This preference is consistent with the findings of most studies on NFPs [3,5,21,42,43]. At the same time, it is worth noting that Wendel et al. [44] found similar results, explaining that people tend to visit urban parks or go on outings during weekends and holidays. Regarding demographic variables, education level ($p < 0.001$), age ($p < 0.001$), marital status ($p < 0.05$), occupation ($p < 0.001$), and income ($p < 0.001$) have significant impacts on visits to NFPs (Table 3). The results show that as age decreases, the proportion of respondents choosing to visit NFPs on weekdays significantly decreases, likely due to the busy schedules of younger residents [32]. This phenomenon is not limited to young adults; many children face similar issues. In China, children under the age of 12 account for 14.28% of the total population. Different educational policies and competitive mechanisms place greater pressure on these children, and the burden of homework and extra tutoring reduces their opportunities to visit urban green spaces on weekdays [45]. However, residents with university education tend to prefer visiting green spaces on weekends, holidays, and during their free time [46,47]. Additionally, there are differences among occupations; self-employed individuals are more likely to visit green spaces on weekdays compared to those in other professions because they have more control over their time.

Most residents prefer visiting NFPs in the morning ($n = 303$) and afternoon ($n = 264$) (Table 2), which also indicates a greater sense of safety during daylight hours [48–50]. According to data from the renowned American polling organization Gallup, China's safety index ranks third globally [51]. The survey includes aspects such as residents' trust in local police, perceptions of personal safety, and the incidence of theft, assault, or robbery in the past year [52]. The study found significant differences in preferences based on education level ($p < 0.001$), age ($p < 0.001$), marital status ($p < 0.001$), occupation ($p < 0.01$), and income ($p < 0.001$) (Table 3). Education level influences the preferred time of visit; residents with a university education tend to visit in the afternoon, while those with other education levels prefer evening visits. Younger respondents, having limited free time in the morning, prefer visiting NFPs in the afternoon. A survey revealed that this younger demographic is often in the prime of their careers, finding it challenging to maintain a healthy work-life balance [32]. Their fast-paced work schedule leads to insufficient sleep, and only after catching up on sleep during the weekends do they have the energy to engage with nature. In contrast, older visitors prefer morning visits. Single individuals tend to visit in the afternoon, while married individuals prefer morning visits to NFPs. Additionally, different occupations show varying time preferences; students and unemployed individuals prefer afternoon visits, while those in other professions prefer morning visits, aligning with their age-related preferences. Finally, higher-income visitors are more likely to choose morning visits, whereas lower-income visitors prefer afternoon visits.

A separate study reveals that the majority of Danes prefer to be in parks during the afternoon [53]. This tendency is consistent with cultural norms in Western nations, where it is typical to sunbathe or spend time in the sun, especially in the summertime. This insight also applies to Nordic nations like Finland, where temperatures are often cool and sunshine is greatly valued [54]. In contrast, urbanites in Singapore and Malaysia, both tropical countries, prefer to visit urban parks on vacations and weekdays, particularly in the morning and evening. This preference is influenced by the tropical climate of Malaysia, which is characterized by high humidity and temperature year-round. Spending time in parks, especially during the afternoon, can be uncomfortable due to these weather conditions. A similar observation was reported in a different investigation on urban greenery usage in Kuala Lumpur [55,56].

Visitors typically spend 1 to 2 h (n = 265) and 2 to 3 h (n = 241) in NFPs, with few staying over 4 h or less than 1 h (Table 2). This moderate duration allows for relaxation and reflects the vastness of NFPs, which are difficult to explore fully in a short time. This study found that only education level ($p < 0.001$), age ($p < 0.001$), marital status ($p < 0.001$), occupation ($p < 0.001$), and income ($p < 0.001$) significantly affect the duration of stay (Table 3). Visitors with high school and university education prefer to stay for 1–2 h, while those with postgraduate education are more inclined to stay for 2–3 h. Younger visitors aged 18–30 usually stay for 1–2 h, whereas middle-aged and older visitors prefer to spend more time. This might be because younger individuals have more energy to complete their visit quickly, while older visitors move at a slower pace and seek more time to connect with nature due to their busy work and life schedules [57,58]. Married individuals tend to stay longer in the parks, possibly because they accompany elderly family members and children who need fresh air [59,60]. Similarly, self-employed individuals and high-income groups, with their flexible schedules and financial independence, are able to extend their visits to the forest parks.

The primary mode of transportation for visitors to NFPs is cars (n = 453). Research indicates that gender ($p < 0.05$), household registration ($p < 0.001$), education level ($p < 0.001$), age ($p < 0.001$), marital status ($p < 0.001$), occupation ($p < 0.001$), and income ($p < 0.001$) significantly influence transportation choices. Women are more likely than men to use public transportation, possibly because men tend to have better directional skills and, therefore, prefer driving. Non-local visitors are more inclined to use public transportation compared to locals, who are more familiar with local routes. Very few visitors choose to travel by motorcycle, which contrasts sharply with the situation in Malaysia, possibly due to the unique traffic regulations in China [55,56]. Visitors with postgraduate education are more likely to ride electric bikes to NFPs than those with lower education levels, possibly due to greater environmental awareness. Younger visitors prefer to ride bicycles, which aligns with their youthfulness, energy, and enthusiasm for exercise. Married individuals are more likely to drive to the parks, as they often spend more time traveling with their families [55,56]. Unemployed individuals prefer public transportation to save on expenses, whereas higher-income visitors prefer driving and seldom choose public transportation. The reason for this is that NFP is on the outskirts, far from residential areas. This outcome was comparable to that of a study on the use of urban parks in Kuala Lumpur [61]. The primary explanations for why Malaysians drive to parks are shorter commute times, lower costs, and affordable gasoline [62]. Inadequate accessibility to public transportation and a lack of acceptable routes were two more concerns that discouraged Malaysians from using public transportation as their primary means of mobility [62]. Similar difficulties confront Italians in Bari, where insufficient transport options have forced residents to rely on vehicles or walk to reach greenery [63].

Overall, most visitors take between 10 min and 1 h to reach NFPs, with few arriving within 10 min (Table 2). This means visitors need more time to get to the NFPs. Research shows that household registration ($p < 0.001$), education level ($p < 0.001$), age ($p < 0.001$), marital status ($p < 0.001$), occupation ($p < 0.001$), and income ($p < 0.001$) significantly affect travel time (Table 3). Visitors without local household registration need more time to reach

the parks, likely due to the greater distances they must travel. Those with junior high school education or lower also tend to take longer to arrive at NFPs. In terms of occupation, students, unemployed individuals, and pensioners spend more time traveling to the parks. Previous studies have extensively examined the relationship between park proximity and park use, with a predominant focus on research conducted in the Global North. However, there has been a relative lack of attention given to exploring the potential interactions between park proximity and park use, despite their significance within the socio-ecological frameworks that guide many studies [1]. A recent study involving nearly 8000 residents from eleven cities in 10 countries across Central and South America aimed to investigate the associations between perceived park proximity and park use. The findings of this study confirm positive correlations between perceived park proximity and park use [1,64,65]. Furthermore, additional studies have also offered supporting evidence in this regard. For example, a Canadian study revealed that park use was more closely related to the amenities and facilities available in the parks than their proximity [66]. Another study conducted in Canada by Lackey and Kaczynski (2009) [67] found no significant association between park-based physical activity and objective or perceived park proximity. However, it did indicate that such physical activity was more likely to occur when objective and perceived proximity were aligned. To gain a better understanding of these associations, further research in this region is warranted. Future studies should employ more sophisticated objective and perceived park measures that effectively capture the diverse features and attributes of parks.

The vast majority of visitors live far from the NFP, with distances of 5–10 km (n = 305) and over 10 km (n = 205) being the most common (Table 2). This is because NFPs are typically located in suburban or rural areas, far from residential zones. Research indicates that household registration ($p < 0.001$), education level ($p < 0.001$), age ($p < 0.001$), marital status ($p < 0.001$), occupation ($p < 0.001$), and monthly income ($p < 0.001$) significantly affect the distance from the NFP (Table 3). Visitors without local household registration live farther from NFPs, which corresponds with their longer travel times. Visitors with a bachelor's degree or higher also tend to live farther from the parks, likely because they usually work in urban areas. Married individuals live farther from the parks, possibly due to their preference for settling in urban areas. Additionally, those with a monthly income exceeding 6000 yuan tend to live farther from NFPs.

As shown in Table 2, there is a significant difference between visitors who go to NFPs alone (6.69%) and those who go with companions (92.01%). Research indicates that gender ($p < 0.001$), household registration ($p < 0.001$), education level ($p < 0.001$), age ($p < 0.001$), marital status ($p < 0.001$), occupation ($p < 0.001$), and income ($p < 0.001$) significantly influence these preferences (Table 3). Compared to women, men are more likely to visit NFPs alone, possibly because women are more concerned about safety when traveling alone. Locals are more inclined to visit alone than non-locals due to their familiarity with the environment and a greater sense of security. Those with university degrees or higher prefer to visit the parks with their families. Young people aged 18–30 are more likely to visit with friends, while middle-aged and older visitors prefer to visit with family members. Single individuals are more likely to go with friends, whereas married individuals tend to visit with their families. Students prefer to go alone or with friends, whereas working individuals are more likely to visit with their families. Higher-income individuals tend to visit the parks with their families, while lower-income individuals are more likely to go alone or with friends.

The preference for visiting parks with family and friends rather than alone or with pets significantly influences visitor satisfaction and park usage patterns by fostering social engagement, which is often linked to higher levels of enjoyment and fulfillment [67–69]. Group interactions enhance the park experience through shared activities and emotional connections, potentially leading to increased satisfaction and higher rates of return visits [11,59]. Additionally, groups can support each other during difficulties or emergencies, further enhancing their experience. This trend may result in higher occupancy during

weekends and holidays, potentially causing congestion in popular areas. Increased demand for group-friendly amenities, such as picnic areas, children's playgrounds, multi-functional rest areas, and sports facilities, may guide the allocation of park resources and infrastructure development [11,59,67]. However, group activities also require more resources for management, maintenance, and safety measures, such as increased patrols and emergency services [11,55]. On the other hand, this preference could marginalize solitary visitors or those with pets, who might seek quieter spaces but find fewer areas suited to their needs, leading to varying satisfaction levels across visitor demographics [11,55,59]. To address this, parks may need to provide designated quiet zones or pet-friendly areas to ensure a fulfilling experience for all. Ultimately, these preferences can foster a sense of community, encourage repeat visits, and shape park design and management to optimize space utilization, enhance the visitor experience across different groups, and ensure equitable access to facilities, contributing to the park's long-term sustainability and appeal.

The lower percentages for traveling alone or with pets may suggest that people prefer to have companionship or assistance during their travels, as they might require support or care along the way. This is comparable to previous research on the cultures of other nations and regions, especially the Italians [13], Malaysians [11], Rotterdam [70], Turks [71], Hispanics [72], and Latinos [12,44], where the majority of these residents like to attend urban parks in large groups with family, friends, or dogs. However, white Americans who use parks are different since 88% of them go alone or with only one other individual [73]. A similar pattern was observed among white park users in a Los Angeles survey, when more than half of them frequented parks individually [72]. This trend was also observed among Dutch park visitors, who preferred to go alone, in pairs, or in small groups [74]. Several studies have found that either the presence or lack of an accompanying person influences the enjoyment of various surroundings for psychological healing. People in urban areas often prefer the company of a friend for a variety of reasons, including safety [75]. However, when safety is not an issue, the lack of a companion also improves rehabilitation. This conclusion is reinforced by other studies, which also show that women, who often experience more fear than men, prefer to visit NFPs with family members or other people compared to going alone [55].

The interplay between social and environmental factors is fundamental to shaping visitor usage and safety perceptions in national forest parks. By comprehensively understanding these factors, park management can implement targeted strategies to improve visitor satisfaction, safety, and overall park utilization. This holistic approach ensures that national forest parks continue to serve as safe, enjoyable, and accessible spaces for all visitors.

4.2. Factors Influencing Safety Perceptions in NFPs

One of the elements impacting the use of urban green spaces is safety, notably the fear of crime [11,61]. The park safety components likely encompass several critical aspects, including the assessment of physical infrastructure such as trails, signage, and facilities, all of which contribute to visitor safety [59,76,77]. Additionally, the study may examine the effectiveness of safety communication strategies, such as the dissemination of information about park rules, wildlife, and potential hazards [59,78]. Visitor behavior, preparedness, and adherence to safety guidelines are also crucial components, alongside the evaluation of emergency response mechanisms and visitors' perceptions of safety, all of which can significantly influence their overall experience and willingness to return [55]. Previous research has also indicated that women are less likely to attend urban parks than men due to concerns about safety [78]. According to a study conducted by Sanesi and Chiarello in 2006 [63], nearly 50% of the citizens of Bari, Italy, expressed a sense of insecurity while visiting their local urban parks. A further survey conducted in Atlanta and Philadelphia in the United States likewise revealed significant apprehension among locals over the safety of parks [63].

Respondents were questioned regarding their feelings of safety while using the NFP (refer to Table 4). It is noteworthy that approximately 90% of the respondents in this study expressed feeling safe in the NFP. This is due to the fact that a majority of the respondents frequent the parks in groups, either accompanied by their relatives or friends. This is in stark contrast to the findings of the forest park study in Malaysia. In Malaysia, park users at forest park had previously experienced or heard of unwanted incidents such as theft, vandalism, and abduction [11,59,79]. This makes the visitors feel unsafe. In addition, the condensed structure of cities and the high concentration of people have led to the extensive utilization of urban green areas as a response to safety concerns [13]. This study was conducted during the day, not at night, and different results might be obtained if conducted at night. Table 5 illustrates the differences in safety perceptions of visitors to NFPs among various demographic groups. The impact of gender and household registration on the perception of safety in NFPs is minimal ($p > 0.05$). Regarding educational attainment, visitors with primary education or below (B = −2.407, OR = 0.090, $p < 0.05$) and university students (B = −0.434, OR = 0.090, $p < 0.01$) exhibit greater concern for safety in NFPs and feel safer compared to those with postgraduate education. In terms of age group, visitors aged 18–30, 31–45, 46–55, and 56–65 years (OR = 27.201, $p < 0.001$; OR = 37.175, $p < 0.001$; OR = 55.472, $p < 0.001$; OR = 188.270, $p < 0.001$, respectively) report feeling safer than older visitors. This indicates that safety concerns increase with age when visiting forest parks. Younger to middle-aged visitors feel safer because they are generally healthier, more physically capable, and possibly more confident in dealing with any potential risks in forest parks, while older visitors feel less safe due to concerns about physical limitations and higher perceived vulnerability. At the same time, this is due to the wisdom and knowledge acquired over the passage of time. Several park visitors at that particular park have previously encountered or witnessed acts of theft, vandalism, and abduction. Individuals might undergo vicarious victimization, wherein they may feel the same emotions as if they were directly victimized when they learn about the criminal experiences of others [13,59].

Regarding occupations, those employed in occupations other than private sector positions (B = −0.831, OR = 0.435, $p < 0.05$) feel safer, whereas private sector employees might experience more stress and insecurity, affecting their overall sense of safety. In terms of occupation, unemployed individuals (B = 1.725, OR = 5.615, $p < 0.05$) are more concerned about safety and find it more difficult to feel secure in forest parks compared to those in other professions. Unemployed individuals might have heightened anxiety and stress due to financial instability, making them more sensitive to safety concerns. Finally, with respect to monthly income, visitors earning less than 3000 yuan (B = −0.620, OR = 0.538, $p < 0.1$) and those earning between 6001 and 10,000 yuan (B = −0.579, OR = 0.560, $p < 0.05$) are more concerned about safety and feel safer compared to visitors with an income exceeding 10,000 yuan. Lower-income visitors might be more cautious due to their daily challenges, leading to heightened awareness. In contrast, higher-income individuals might have higher expectations and feel more entitled to better safety standards. These explanations suggest that perceptions of safety in NFPs are influenced by a complex interplay of physical capabilities, life experiences, and socioeconomic factors.

In conclusion, the observed differences in safety perceptions among various demographic groups visiting NFPs can be attributed to several factors. The minimal impact of gender and household registration suggests universal safety concerns. Individuals with primary education or below, as well as university students, might feel safer due to lower expectations or better awareness of safety guidelines. Younger to middle-aged visitors generally feel safer due to better physical health and confidence, while older individuals may feel more vulnerable. Single visitors might experience heightened vulnerability compared to divorced individuals, who feel more resilient. Employment status influences perceptions, with those in stable occupations feeling safer than private sector employees. Unemployed individuals tend to be more anxious about safety due to financial instability. Lastly, lower-income visitors might be more vigilant and cautious, contributing to a heightened sense of safety, whereas higher-income visitors might have higher safety expectations and feel less

secure when these are not met. These findings highlight the complex interplay of physical capabilities, life experiences, and socioeconomic factors in shaping safety perceptions.

5. Conclusions

NFPs play a crucial role in the construction of urban ecological environments, directly impacting residents' quality of life by providing opportunities for leisure, recreation, and connection with nature. However, with societal progress, issues such as severe urbanization and the diminishing availability of urban green spaces are becoming increasingly prominent. This research uses a conceptual framework based on a socio-ecological approach to analyze the usage and safety perception experiences of national forest parks, comparing them with forest parks in other countries. The findings reveal significant differences between NFPs in different cultural contexts. Urban residents are the primary users of NFP green spaces. Residents tend to visit NFPs in the morning and midday, which differs from the usage patterns of forest parks in other regions. This behavior is mainly related to residents' sense of security and climate conditions. Most visitors prefer nature, relaxation, and spending time with family, often traveling to NFPs by car. However, there is also a segment of young visitors who prefer to visit NFPs alone or with friends.

This survey suggests that park facilities should be diversified to meet varied visitor needs. Areas with high demand for family and group activities should include additional spaces like picnic areas, barbecue spots, and children's playgrounds. Recreational facilities such as viewing platforms, trails, and sports venues should be added to cater to all age groups. For safety, the installation of emergency rescue facilities, including first aid stations, emergency telephones, and AEDs, along with clear signage, maps, and safety reminders, is recommended. Visitor service centers would further enhance safety and convenience. To manage visitor flow, a reservation system or timed entry could prevent overcrowding. Expanding natural education programs, such as guided tours, nature classes, and ecological lectures, would promote environmental awareness, while interactive experiences like ecological zones, animal and plant viewing areas, and outdoor adventures can boost engagement.

To minimize environmental impact, the park should include protected and ecological restoration areas, increase recycling facilities and eco-friendly restrooms, and promote sustainable behaviors. Efficient resource management, green energy promotion, and sustainable material use should be prioritized to reduce the park's ecological footprint. Exploring the utilization of NFPs and improving park systems are essential for promoting urban development, enhancing the urban landscape, and preserving cultural heritage. Government departments should focus on the real needs of local residents and prioritize the creation of a forest park environment that fosters harmonious coexistence between humans and nature.

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Article

Deciphering Motorists' Perceptions of Scenic Road Visual Landscapes: Integrating Binocular Simulation and Image Segmentation

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Abstract: Traditional scenic road visual landscape assessment methods struggle to quantify drivers' subjective visual perceptions. This study aims to develop a new method to decipher Scenic Road Visual Landscape Evaluation (SRVLE) of motorists' visual field, reconciling the longstanding subjectivity–objectivity dichotomy in landscape quality research. By adopting binocular visual simulation and image segmentation, this paper conceptualizes a novel "non-scale semantic differential approach" to quantify landscape qualities across the dimensions of naturalness–artificiality (NA), diversity–coherence (DC), and openness–deepness (OD), constructing a three-dimensional visual landscape quality evaluation system. Taking the Nujiang Beautiful Road in Yunnan as a case study, the results show the following: (1) The three indicators reveal the scenic road's distinctive visual landscape characteristics, marked by high naturalness, coherence, and relative openness. (2) SRVLE is found to vary between the two driving directions and different sections. (3) The three-dimensional evaluation cube intuitively displays the comprehensive characteristics of landscape quality, providing a basis for scenic road planning. This method offers a new approach to resolving the subjective–objective divide in SRVLE and can assist road administrations in enhancing policy planning, construction, and management, thereby promoting the high-quality development of scenic roads.

Keywords: scenic road; visual landscape evaluation; field of view; image segmentation

1. Introduction

Scenic roads are recreational transportation routes built by leveraging natural corridors such as mountains, rivers, and heritage corridors including ancient city walls and trade routes. They are the product of the integration of transportation, tourism, and landscape [1,2] and are considered an antidote to monotonous travel [3]. Scenic roads built upon roadside landscape resources can provide countryside driving experiences and nature tourism services, allowing the "charm value" of the road to surpass its "mobility value", with the road itself becoming a destination [2]. In developed countries, scenic roads have evolved from parkways, initially serving horse-drawn carriages and then experiencing rapid development after the invention of the internal combustion engine [4]. With the development of the transportation industry, scenic roads have extended the leisure travel activities of urban residents from city parks to suburban and national park areas [5], such as the Blue Ridge Parkway in the US in the 1930s and the German Alpine Road. However, in developing countries, transportation has developed prior to the leisure tourism industry, and the two have long remained in a state of separation. Roads often fail to showcase the beautiful landscapes along the way and may even damage the natural scenery due to

construction work, hindering the development of the tourism industry [6,7]. In recent years, some developing countries have begun to attach importance to the significance of scenic road construction, seeing it as an effective economic means to achieve the integration of landscape resources and coordinated regional development, and it has even been regarded as an important national development strategy in China [8].

Roadside landscapes are the core resources of scenic roads, comprising the comprehensive whole of all land and the spatial and material elements on the land that are within the driver's line of sight [9]. For self-driving travelers, from the perspective of the mobility experience, the landscapes and spaces change with the travelers' movement and are the primary source of travel pleasure [10]. Therefore, improving the visual landscape quality of scenic roads is the main goal of their construction, and evaluating the visual landscape quality is the foundational work and basis for the planning, construction, and management of scenic roads [3,9,11].

1.1. Objectivity vs. Subjectivity in Scenic Road Visual Landscape Evaluation (SRVLE)

Similar to the general understanding of visual landscape evaluation, the SRVLE is also divided into expert and public paradigms based on the type of evaluator [12,13]. The expert paradigm prioritizes the objective expression of the physical characteristics of the road landscape, focusing on the scientific rigor and accuracy of visual landscape quality research [14]. The public paradigm prioritizes the subjective expression of the perceived experience of the road landscape, focusing on the humanistic nature and public benefit of visual landscape quality [15].

The expert paradigm originated in the 1960s [16], with professionals from various fields such as transportation, design, ecology, commerce, and tourism objectively evaluating the physical attributes of the landscape elements, such as form, color, line, and space, combined with available information on topography, climate, and biodiversity [14]. This often involves multiple complex aspects such as scenic value, natural value, historical value, recreational value, and cultural value [17,18]. The first set of expert evaluation systems for road landscape was the Visual Impact Assessment (VIA) established by the US Federal Highway Administration in 1986, which was later introduced into the US National Scenic Byway Program, marking the standardization of the scenic road evaluation process [16,19]. In China, the expert paradigm was introduced to the scenic road field around 2000: scholars such as Wu Bihu invited a panel of 10 experts from related fields to use the "equidistant expert group visual assessment method" to conduct on-site investigation and evaluation of the natural landscape, cultural landscape, viewshed, and visual quality of the Xiao Xing'an Mountains Scenic Road every 1 or 2 km [20]. Although the expert paradigm's evaluators are also human beings who need to establish multi-dimensional indicators and score through field investigations and data collection [21], at this stage, the "human" is merely a "professional machine" under the evaluation standards, striving to completely eliminate subjective emotions and make objective physical descriptions [22]. With the development of geographic information technology, remote sensing imagery, land cover, and elevation data have been used for objective quantitative analysis of visual landscape quality [23]. RVLQA often focuses on spatial feature analysis [24] or visibility calculation [22] or combines viewshed analysis results with landscape characteristics such as land use and ecological patterns to provide a quantitative basis for planning and design [25]. For example, Anderson et al. conducted viewshed analysis based on the digital surface model (DSM) generated from LiDAR data to evaluate the visual landscape quality of the Blue Ridge Parkway in terms of the visibility of various landscapes during the driving process, thereby managing the roadside landscape [26]. The introduction of geographic information methods has made the expert evaluation process less subject to the interference of personal subjective perception; accordingly, they are considered a more scientific set of methods [27], and due to the standardization and universality of the methods, they have been promoted in various countries as the official procedures for scenic road assessment and construction [18,28].

The public paradigm holds that the perceived authenticity of visual landscapes is more important, and the remote sensing and other materials used in the expert evaluation have a large difference in perspective from the users; therefore, they cannot represent the public's perception [29,30]. Clay and Smidt [3] have demonstrated that the public and experts have different focuses in road landscape evaluation and even show different preferences for the same evaluation content. Therefore, the public paradigm believes that visual landscape quality is the joint product of the specific (visible) characteristics of the landscape and the psychological (perceptual, cognitive, and emotional) processes of the human observer; without an observing subject, there is no visual landscape, and the evaluation results need to be based on the subjective aesthetic values of the people [31,32]. The paradigm of public evaluation is to express the subjective feelings of the users, using photos, images, etc., as the presentation medium and relying on surveys, scales, etc. to obtain a visual landscape quality evaluation [15,25]. For example, Kent and Elliott [17] took photographs of a scenic road in Connecticut, USA, and invited 177 residents along the route to score the selected photographs to obtain information on the landscape quality of that road segment. Matijošaitienė and Stankevičė [33] established a web-based questionnaire with multiple sets of conceptual semantic differentials, such as "interesting–boring", "natural–artificial", and "harmonious–chaotic", and invited subjects to evaluate 288 road landscape photos along 12 major European traffic routes in Lithuania. The evaluation methods of the public paradigm based on questionnaires and scales have been criticized by the expert paradigm: (a) there are quite obvious subjective differences between different groups and even individuals within the same group [15,31]; (b) the scales used in most studies have a large span and ambiguous expression, and their reliability and validity are difficult to verify [32,34]. Therefore, the expert paradigm criticizes the RVLQA of the public paradigm as being difficult to quantify, unscientific, and unable to support the needs of planning and construction [22,35].

The "objectivity of evaluation" in the expert paradigm and the "subjectivity of experience" in the public paradigm have become two sides that cannot be reconciled in the process of exploring the visual landscape quality of scenic roads. Some studies have attempted to integrate the advantages of the two paradigms. For example, Martín et al. [25] have combined the observer's perspective with the traditional landscape planning perspective, using photos to supplement the attributes that are difficult to observe from flat maps, and believe that the expert paradigm with the assistance of the public paradigm can provide more detailed references for road planning and design. However, such methods only use the two paradigms simultaneously and have not achieved the objective quantification of subjective visual perception; therefore, the results obtained from the two paradigms may contain contradictions. Some scholars working with the public paradigm, based on the "stimulus–response" principle [14], have conducted quantitative analysis of the visual preferences of scenic road visitors through eye movement data, EEG, ECG, and other physiological indicators in an attempt to objectively express subjective perceptions, and they believe that this method can scientifically and accurately serve in the planning and construction of roadside landscapes [9]. However, this method confuses aesthetic preferences and visual perception; it quantifies physiological signals to measure preferences but does not quantify the visual landscape elements themselves. As a result, it remains unclear how to relate preferences to landscape quality or control the quantity and quality of visual landscape elements in planning and design. In recent years, the rapid development of the computer vision field has provided new intelligent tools for visual landscape research, which have been widely used in urban street environments to quantitatively describe street landscape characteristics such as the green view index and the sky view factor [36,37]. However, such studies rely on street view big data and have not applied their methods to scenic roads.

1.2. Eye Range vs. Proportional Reality: Expressing the Visual Landscape

Images, as authentic records and remote representations of landscapes, are an important medium for visual landscape evaluation for both the expert and public paradigms [38]. However, how to comprehensively and scientifically express visual landscapes through photographs has not yet been resolved. Some studies suggest that a 50 mm focal length camera lens can provide an experience similar to the human eye, with a more natural perspective effect [39,40]. Therefore, some visual landscape evaluation studies have used this focal length to collect image data [3,41,42]. However, the actual field of view of this focal length is significantly narrower than that of the human eye (only 60° of view) and can only record limited visual information [43]. A comparative study found that the visual landscape evaluation based on ordinary camera photos had obvious differences from on-site perceptual evaluation and attributed this to the incomplete expression of the scene by photos [44]. Therefore, some scholars believe that panoramic images can cover the full range of human vision and are more suitable as a medium for landscape visual evaluation [21]. Panoramic images have gradually been widely adopted in the field of visual landscape research [45–47] and have also been used in audits of built urban street environments [48,49]. However, in reality, untreated panoramic images have large distortions, and the image content is distorted, with incorrect proportions of various elements, deviating significantly from real human visual perception [50]. Pardo and Mérida [51] shot multiple overlapping photos from the same viewpoint and then stitched them into a super-wide-angle image to eliminate the distortion of a single shot in order to evaluate the visual landscape of a roadside viewing point in Spain. There has also been research in which photos were taken in four directions (north, east, south, and west) from the same viewpoint (without stitching them together) to fully present the visual landscape of a street scene [52]. However, these methods have large data volumes and complex processing, and the latter method divides the landscape scene into different pictures, causing discontinuity in the visual experience during the evaluation process. Virtual reality (VR) scenarios can be created using panoramic images or 3D modeling, allowing evaluators to be immersed and obtain a comprehensive view. Gandy and Meitner [53] introduced VR scenarios into the evaluation process to help subjects accurately perceive and express their visual experience of a scenic road, but such methods have higher time and monetary costs, making them difficult to popularize [54]. The media for visual landscape evaluation are constantly pursuing true simulation of human visual perception, but there are few cases that can effectively simulate the human binocular visual experience. Little research has started from the physiological characteristics of human binocular vision to produce visual landscape evaluation images that are closest to the human visual field.

Based on the identified research gaps, this study aims to break through the limitations of the two existing research paradigms in the field of SRVLE. On one hand, from the perspective of visual physiology, it will collect scenic road image data based on the characteristics of the binocular field of view (FOV) to address the subjectivity of the viewing experience. On the other hand, it will utilize semantic segmentation to process the images, ensuring the objectivity of the evaluation data through pixel-level analysis of object information. This study will empirically apply the new SRVLE methodology to the Nujiang Beautiful Road in Yunnan, China. The main steps include road image acquisition, integration of the human eye's FOV, image segmentation, and perception indicator calculation to analyze the visual landscape quality as perceived by self-driving travelers. This research will provide value for scenic road landscape evaluation and management, and it also has broad applicability in the field of environmental assessment.

2. Materials and Methods

2.1. Study Area

The Nujiang Beautiful Road is a scenic route spanning approximately 282 km within the Three Parallel Rivers Protected Areas, a UNESCO World Heritage Site, adjacent to the China–Myanmar border. The northern terminus of the road is located in Bingzhongluo

Town, Yunnan Province, China (28.013333° N, 98.628471° E), while the southern end lies in the northern outskirts of Lushui City (25.904833° N, 98.833333° E). Traversing the Hengduan Mountains region, this 282-kilometer stretch is characterized by rugged terrain featuring four mountains and three rivers. This winding high-altitude road offers drivers the opportunity to appreciate the renowned Nujiang Grand Canyon, known for its scenic beauty. The canyon presents impressive landscapes including forests, rivers, glaciers, and high-altitude karst formations (Figure 1). Since 2017, the local government has invested over RMB 7 billion to improve road infrastructure, enhance tourist facilities, and upgrade the scenic beauty of the road, thereby enriching the tourist experience [55]. As this location is a designated scenic road tourist destination, its landscape resources warrant attention.

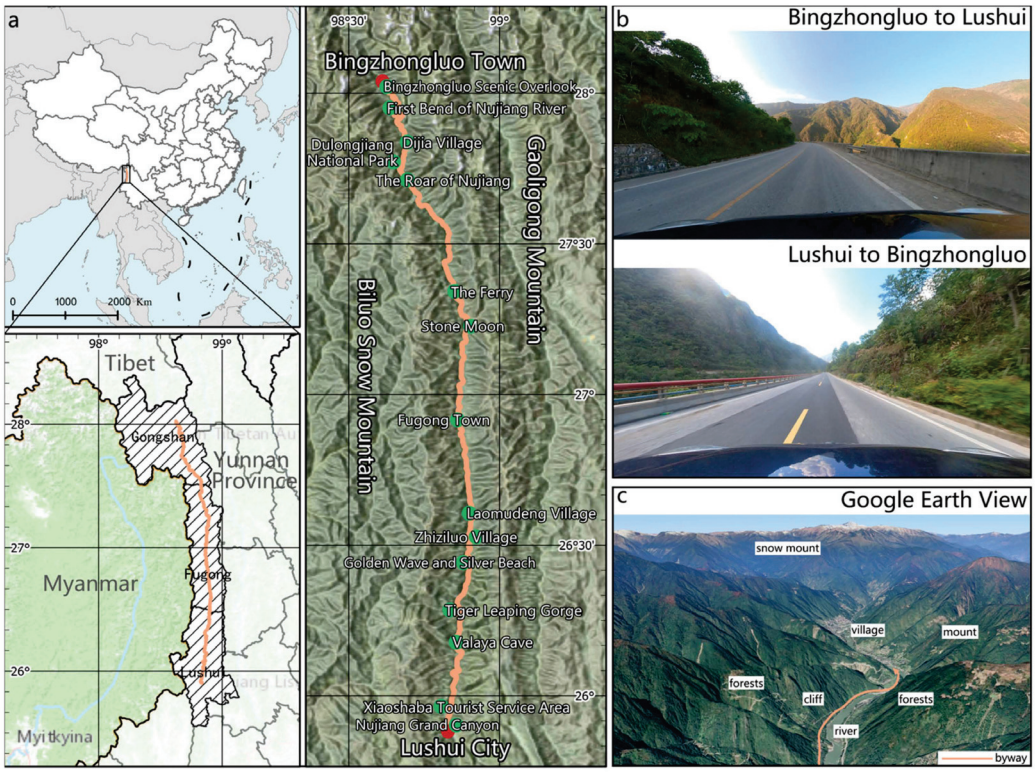


Figure 1. Overview map of the study area. (**a**) Geographic location of the study area. (**b**) Actual image of the Nujiang Beautiful Road. (**c**) Three-dimensional terrain image of the Nujiang Beautiful Road.

2.2. Image Acquisition and Simulation of the Human Eye's Field of View

2.2.1. Acquisition Equipment

To address the incompleteness of using regular photographs in place of the human eye's field of view and the one-sidedness of the landscape evaluation results, a convenient, fast, and low-cost simulation method for the human eye's field of view is proposed. According to visual physiology research, the binocular visual range of a person generally refers to the entire spatial range observed by the human eye within the horizontal and vertical planes, with the head and eyes fixed and not rotating [56,57], and the normal adult's monocular visual field is generally 150° horizontally (60° inward and 90° outward from the cheek) and 125° vertically (55° downward and 75° upward). The binocular visual field has about 120° of overlap in the horizontal direction, resulting in a 180° horizontal and 125° vertical visual field [58].

This study selected the Insta360 ONE X2 action camera (X2 camera) as the image acquisition device for the roadside landscapes of the Nujiang Beautiful Road. This device has been applied in urban and suburban environments and has shown good acquisition performance [59,60]. The X2 camera has an equivalent focal length of 7.2 mm and can capture 360° panoramic photos in both the horizontal and vertical directions when both

the front and rear lenses are working. Although the images have significant distortion around the edges, the central area retains good perspective realism, and this perspectively accurate imaging area is larger than the human eye's field of view. Additionally, this action camera has the following advantages: (1) it is small, portable, and easy to install and firmly mount on the vehicle; (2) it has excellent motion capture capabilities, ensuring high-quality imaging under high-speed and vibration conditions; (3) it has a mobile app control function, providing convenience for in-vehicle shooting; (4) it has a GPS function, effectively recording the shooting location; (5) it has good waterproof and dustproof performance, ensuring high reliability in complex shooting environments.

2.2.2. Bidirectional Equidistant Photo Acquisition

Previous visual landscape quality evaluation studies have used photos selected subjectively by researchers [15,25,33], which has affected the comprehensiveness and objectivity of road quality expression, and may have led to biased evaluations by participants. This study uses a bidirectional equidistant photo acquisition method to comprehensively present the road landscape environment. Regarding the selection of shooting distance, relevant visual physiology research has shown that the human eye can distinguish the color and form of objects at a distance of 1 km but cannot clearly distinguish the outlines of landscape entities beyond 1 km [61,62]. One previous SRVLE research has also set a 1–2 km observation interval to record the landscape changes along the road [20]. This study adopted a 1 km photo acquisition interval, resulting in 282 sampling points in each direction, which ensured the continuity and accuracy of the road landscape description while maintaining relatively little landscape overlap between adjacent images. Furthermore, regarding the actual driving experience, the Nujiang Beautiful Road has cliffs on one side and the Nujiang River on the other, resulting in differences in landscape experiences in the two driving directions. Therefore, bidirectional acquisition was necessary.

To better present the roadside landscapes, images were collected on weekdays (26–30 April 2021), shortly after the road was newly constructed and opened, to minimize interference from other vehicles. The Nujiang Beautiful Road has a speed limit of 40 km/h throughout its length. During image acquisition, we deliberately maintained a vehicle speed of approximately 30 km/h and ensured a stable posture to minimize vibrations. We also took care to avoid interference from other vehicles on the road. While our target image acquisition interval was 1 km, slight variations of a few dozen meters were necessary in some cases to maintain a distance from the preceding vehicle. Additionally, the camera was fixed at a height of 1.2 m above the ground, perpendicular to the vehicle's hood, to match the typical eye level of a driver. The camera parameters were set to 360° panoramic shooting, with GPS positioning enabled and other parameters kept consistent to reduce differences in image quality.

2.2.3. Synthesis of Binocular Field of View Images

The panoramic images captured by the X2 camera need to go through four steps, namely, software export, preliminary cropping, distortion correction, and field-of-view simulation, to obtain images that closely match the driver's binocular visual field (Figure 2). The most critical step is to utilize Python's PIL library to apply the visual field range proposed by Ruch and Fulton [58] to crop the research images, retaining only the area within the visual field, thereby obtaining images of the Beautiful Road matching the human eye's field of view.

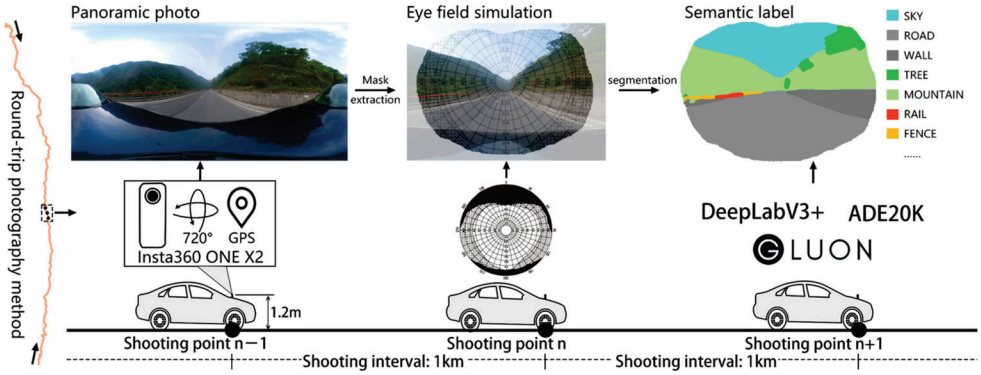


Figure 2. Process for obtaining human visual field images. Acquisition methods, acquisition equipment, visual field simulation, and image segmentation.

2.3. Segmentation of Visual Field Images

Identifying and segmenting the landscape elements in the images is crucial for the objective measurement of scenic road visual landscape quality. This study employed semantic segmentation and pixel analysis to quantify the driver's visual perception, utilizing the Gluon CV toolkit integrated with the DeepLabv3+ model based on Apache MXNet. Gluon CV simplifies model development and offers a range of pre-trained models, including DeepLabv3+, which is known for its accuracy and efficiency, especially in road scene segmentation [63]. When tested on the ADE20K dataset, DeepLabv3+ outperformed other models such as PSPNet and SegNet, achieving 82.1% pixel classification accuracy [63]. This approach generates labeled images, enabling precise calculation of area proportions for each landscape element, thereby supporting objective assessments of scenic road environments. The combination of Gluon CV, DeepLabv3+, and the ADE20K dataset has been used to identify street environment elements [52,64].

2.4. Constructing the SRVLE System

To address the reliability issues caused by the coarse intervals of traditional semantic differential scales, this study constructed a "non-scale semantic differential approach". It utilizes pixel-level image calculations to obtain more precise numerical values for detecting scenic road visual landscape quality. To ensure comparability between different dimensions, each concept pair is set as an indicator ranging from 0 to 1, with 0 and 1 representing the two extremes. The terms "high value" and "low value" only reflect the degree of proximity to the maximum or minimum and do not indicate the overall quality level.

In selecting the concepts for the semantic differentials, this study refers to the visual landscape evaluation framework proposed by Ode et al. [65] in the EU project VisuLands, as well as the related content of the US Federal Highway Administration's Visual Impact Assessment (VIA) system [66]. Considering the actual conditions of the case study site and the requirements of photo evaluation, three pairs of semantic differential indicators were finalized: "Naturalness–Artificiality (NA)", "Diversity–Coherence (DC)", and "Openness–Deepness (OD)". These examine the landscape's ecological attributes, compositional elements and spatial characteristics. The definition and calculation method for each indicator are as follows:

2.4.1. Naturalness–Artificiality (NA)

The NA attribute of the landscape refers to the degree of human modification of the natural environment. A more natural and primitive landscape character can evoke a sense of freshness and pleasure for self-drivers [67,68]. However, the quality of the landscape cannot be judged simply by the NA value; well-designed artificial elements, such as service areas and observation decks, can also enrich the driving experience by providing necessary amenities.

In the expert paradigm's environmental audits, geographic information technology is often used to calculate the area and weight of different land cover types to assess this indicator [25,69]. This study constructed the NA perceptual characteristics of the roadside landscape (except the driving road) from the driver's perspective by considering the type of landscape objects and their proportional coverage in the visual field. The landscape objects were divided into natural elements (e.g., trees, shrubs, mountains, and sky) and artificial elements (e.g., buildings, fences, walls, and signs). The ratio of visual coverage between natural and artificial elements reflects the degree of NA in the landscape.

$$NA = \sum_{i=1}^{n} s_{Ni} \tag{1}$$

where n is the number of natural elements and s_{Ni} represents the proportion of the ith natural element in the roadside landscape. NA is the sum of the area proportions of all natural landscape elements. An NA value closer to 1 indicates a more natural landscape.

2.4.2. Diversity–Coherence (DC)

DC measures are commonly used indicators in visual landscape evaluation. In the scenic road driving context, diverse landscapes can enrich the visual experience and relieve visual fatigue and stress [70]. However, excessive elements may reduce harmony and potentially pose safety risks by distracting drivers [71,72]. Additionally, coherent landscapes have a sense of order, but lack of variety can lead to monotony [73].

Most scholars calculated DC based on information entropy theory [74,75]. However, information entropy essentially reflects the uncertainty and discreteness of elements, which is not equivalent to diversity and richness [76,77]. This study calculated DC based on the principles of compositionism [78,79] and introduced the concept of "thematicity" to improve the measurement. DC involves two aspects: (a) Element quantity. The more types of elements, the more diverse the landscape. (b) Element thematicity. Significant differences in the area proportions of elements indicate visually dominant features, resulting in a unified landscape theme. If each element contributes a similar proportion of the FOV, the resulting landscape appears more chaotic.

$$DC = \frac{N}{N_s} - SD \tag{2}$$

where N is the number of element labels in the image, N_s is a constant representing the typical 15 landscape element types in this case, and SD is the standard deviation of the proportions of different labels. A DC value closer to 1 indicates a more diverse landscape.

2.4.3. Openness–Deepness (OD)

The OD reflects the degree of spatial enclosure. Open road spaces can make self-drivers feel relaxed and safe [80,81]. Deep road spaces bring a sense of mystery and focus, causing drivers to concentrate [71]. The calculation of OD depends on the proportion of environmental background within the visual field. In urban studies, OD is calculated using sky visibility [71]. In the scenic road environment, there are no high-density buildings or congested traffic; therefore, the road can also be an environmental background.

$$OD = \frac{S_s + S_r}{S_f} \tag{3}$$

where S_s and S_r are the areas of sky and road in the image and S_f is the total image area. An OD value closer to 1 indicates a more open landscape.

3. Results

3.1. Semantic Segmentation Results

This study set up 282 sampling points in both the Lushui–Bingzhongluo (L2B) direction and the Bingzhongluo–Lushui (B2L) directions. Among the 564 road images captured at all sampling points, 560 photographs were successfully captured (Figure 3), with

four missing in the L2B direction. The missing data occurred due to temporary connectivity issues between the phone and the camera. To maintain the rigor of our analysis, these four missing values were filled using interpolation (average of adjacent values). Due to the round-trip shooting, the two shooting series have opposite geographic shooting orders. The results in the L2B direction are arranged in reverse order to facilitate data comparison.

The image segmentation identified 15 landscape element labels in the case study area: tree, shrub, mountain, water, sky, driving road, other road, building, wall, fence, bridge, bare land, sign, vehicle, power pole/tower, and unidentified (Table 1). It is worth noting the following: (a) Since the vehicle is not a fixed roadside landscape and the labels identified as "undefined" are mainly due to individual errors, these two items were excluded from the index calculation process. (b) The tunnel, a special road scene (road and wall only), has extremely low NA, DC, and OD values, which will have a large impact in the calculation. Therefore, image data taken inside the tunnel were excluded in the specific analysis.

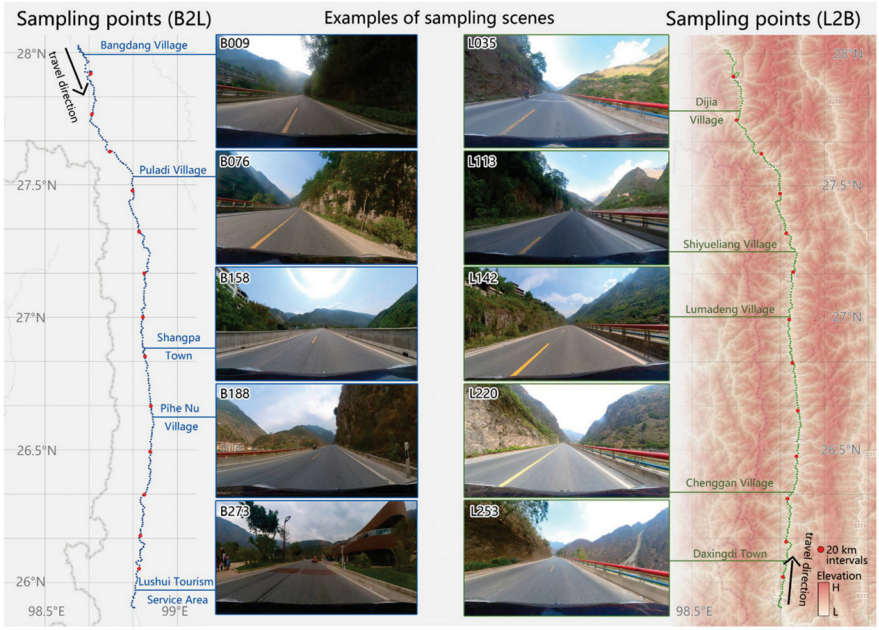


Figure 3. Examples of sampling scenes. The red dots on the map are arranged at 20 km intervals.

Table 1. Semantic segmentation results of Nujiang Beautiful Road landscape labels.

Label		B2L			L2B		
Category	**Types**	**Min/Max**	**Mean**	**SD**	**Min/Max**	**Mean**	**SD**
Natural	Tree	0.0002/0.4109	0.1015	0.0870	0.0000/0.3792	0.0846	0.0671
	Shrub	0.0000/0.1159	0.0095	0.0181	0.0000/0.1680	0.0083	0.0130
	Mountain	0.0001/0.4341	0.2010	0.1043	0.0222/0.4980	0.1894	0.0724
	Bare land	0.0000/0.0831	0.0038	0.0119	0.0000/0.0640	0.0026	0.0079
	Sky	0.1017/0.3725	0.2388	0.0472	0.0778/0.3540	0.2735	0.0406
	Water	0.0000/0.0279	0.0005	0.0030	0.0000/0.0725	0.0043	0.0093
Artificial	Road	0.3218/0.4465	0.3827	0.0180	0.3122/0.4437	0.3863	0.0241
	Building	0.0000/0.2096	0.0082	0.0259	0.0000/0.1984	0.0106	0.0310
	Wall	0.0000/0.1830	0.0260	0.0331	0.0000/0.2441	0.0204	0.0226
	Fence	0.0000/0.0853	0.0103	0.0095	0.0000/0.0561	0.0085	0.0095
	Bridge	0.0000/0.0000	0.0000	0.0000	0.0000/0.0215	0.0001	0.0013
	Sign	0.0000/0.0462	0.0009	0.0040	0.0000/0.0222	0.0006	0.0026
	Pole/tower	0.0000/0.0512	0.0007	0.0042	0.0000/0.0246	0.0006	0.0031
Exclusions	Vehicle	0.0000/0.0711	0.0013	0.0067	0.0000/0.0366	0.0052	0.0037
	Unidentified	0.0001/0.0579	0.0147	0.0122	0.0000/0.0477	0.0095	0.0063

The semantic segmentation results revealed the following: (a) the Nujiang Beautiful Road has a rich variety of landscape elements, but with significant disparities in their proportional coverage within the visual field. Four landscape elements—the driving road, mountains, sky, and trees—occupy over 90% of the visual field, forming the fundamental basis of the scenic road's visual landscape. (b) Among these elements, mountains, trees, and sky exhibit the highest standard deviations in their visual field proportions, indicating the greatest variation and dynamism in the driving experience, providing a more varied visual perception. (c) Comparing the data between the two driving directions, the proportional coverage of the same landscape elements fluctuates slightly, but the differences remain within 3%, suggesting a high degree of similarity in the overall visual landscape characteristics along the case study site.

3.2. NA Evaluation

The evaluation results show that the overall NA value of the Nujiang Beautiful Road is 0.9050 (with L2B at 0.8994 and B2L at 0.9105) (Table 2). The higher NA values along the Nujiang Beautiful Road are concentrated in the middle to late sections of the road (north of Lushui City), as the endpoints of the road are still some distance away from the Lushui city center, where the natural landscape is well preserved. However, as the road passes through several townships along the way, the occasional appearance of villages leads to fluctuations in the NA index, with the lowest NA value reaching 0.5366. Nevertheless, due to the sparse population and low building density in the region, the occurrence of these lower NA values is sporadic.

Table 2. NA index of Nujiang Beautiful Road.

Road Direction	Min	Max	Mean				
			Total	0–25% Section	25–50% Section	50–75% Section	75–100% Section
B2L	0.5366	0.9897	0.8994	0.8894	0.9042	0.8816	0.9228
L2B	0.6334	0.9932	0.9105	0.8970	0.9125	0.9019	0.9305

Overall, the Nujiang Beautiful Road exhibits a high degree of similarity and synchronous changes in the NA values on both sides of the road. However, analysis of the NA heatmap and point density plot (Figure 4) reveals certain differences between the two driving directions. The B2L direction shows a more continuous and concentrated distribution pattern, while the L2B direction has a more scattered distribution with greater fluctuations in NA values. To validate the differences in NA distribution characteristics, kurtosis was calculated. The kurtosis is higher for the B2L direction (8.5023) compared to the L2B direction (5.6591), indicating a more significant clustering of NA values around the mean in the B2L direction.

The B2L side exhibits a higher average NA value. However, the proportions of landscape elements reveal that the B2L direction has smaller visual shares of five natural landscape elements (trees, shrubs, mountains, water bodies, and bare land) compared to the L2B direction. This discrepancy arises because the B2L side lies on the outer edge of the road, nearer to the Nujiang River and farther from the mountains, resulting in a broader sky view and fewer artificial elements interrupting the natural landscape. In contrast, the L2B direction is closer to the mountains and features more road infrastructure (such as retaining walls). Although these elements are also visible from the opposite side, they occupy a smaller proportion of the visual field.

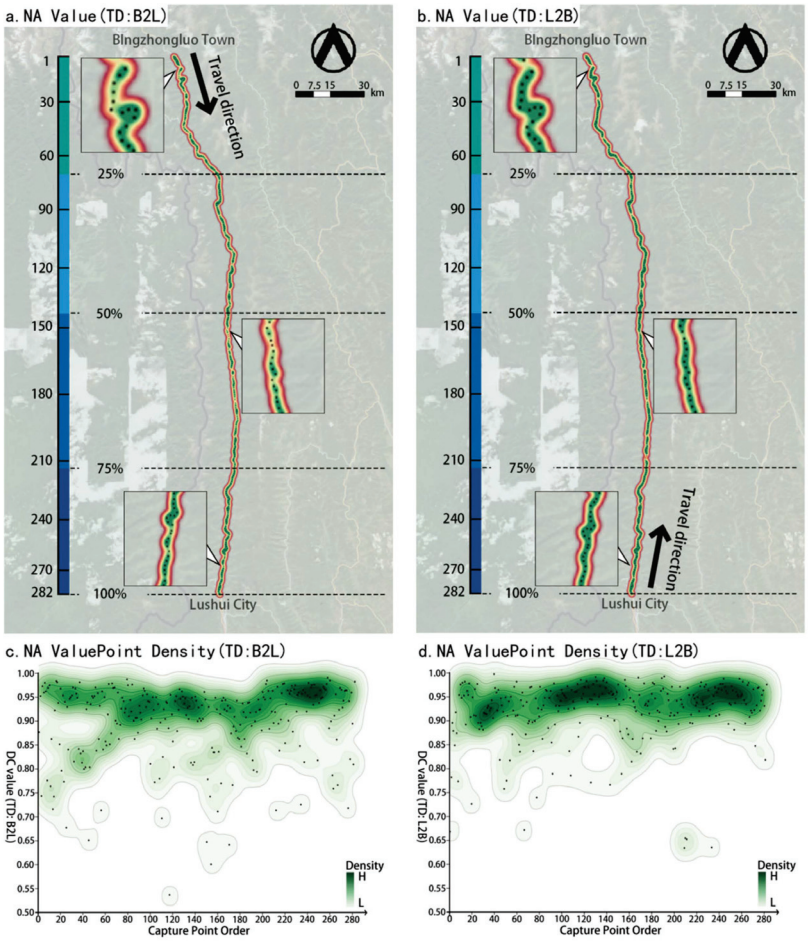


Figure 4. Spatial distribution and density of NA index. (**a**) NA heatmap of B2L direction, (**b**) NA heatmap of L2B direction, (**c**) NA point density of B2L direction, and (**d**) NA point density of L2B direction.

3.3. DC Evaluation

The L2B side has an average of 6.25 elements per image, while the B2L side has 6.79 elements (Table 3). The three dominant theme elements (mountains, trees, and sky) and the two inherent road features (driving road and guardrails) appear frequently and continuously. After excluding these five element types, the additional landscape elements that appear at each sampling point are considered the key factors contributing to visual stimulation. These key factors are mainly water bodies, shrubs, and buildings, which enrich the landscape experience. It can be observed that each image has about one additional key factor. The DC values are 0.2839 for the L2B direction and 0.3198 for the B2L direction, both less than 0.5. Overall, the landscape of the Nujiang Beautiful Road can be characterized as coherent but not lacking in interest.

Table 3. DC index of Nujiang Beautiful Road.

Road Direction	Elements per Image (Mean)	Mean				
		Total	0–25% Section	25–50% Section	50–75% Section	75–100% Section
B2L	6.2545	0.2839	0.2926	0.2793	0.3082	0.2549
L2B	6.7929	0.3198	0.3267	0.3081	0.3375	0.3057

The DC characteristics of the Nujiang Beautiful Road demonstrate significant synchronized changes in both driving directions, exhibiting a rhythmic pattern of "unity–diversity–unity–diversity–unity". This pattern is evident as alternating light and dark areas in the

heatmap (Figure 5), with the point density map also revealing notable fluctuations, indicative of landscape fragmentation. This fragmentation arises from the dispersed distribution of settlements along the route. When dividing the road into four quartile sections, DC values consistently remain higher in the L2B direction than in the B2L direction. This discrepancy is attributed to the proximity of the L2B side to the Nujiang River, where more frequent views of water bodies are available and the open sightlines enable the observation of more landscapes. Conversely, the B2L side's proximity to the steep mountains of the Nujiang Canyon restricts visibility, particularly around road turns. Furthermore, the prevalence of mountain views on the B2L side reinforces the cohesive nature of the mountain-dominated landscapes.

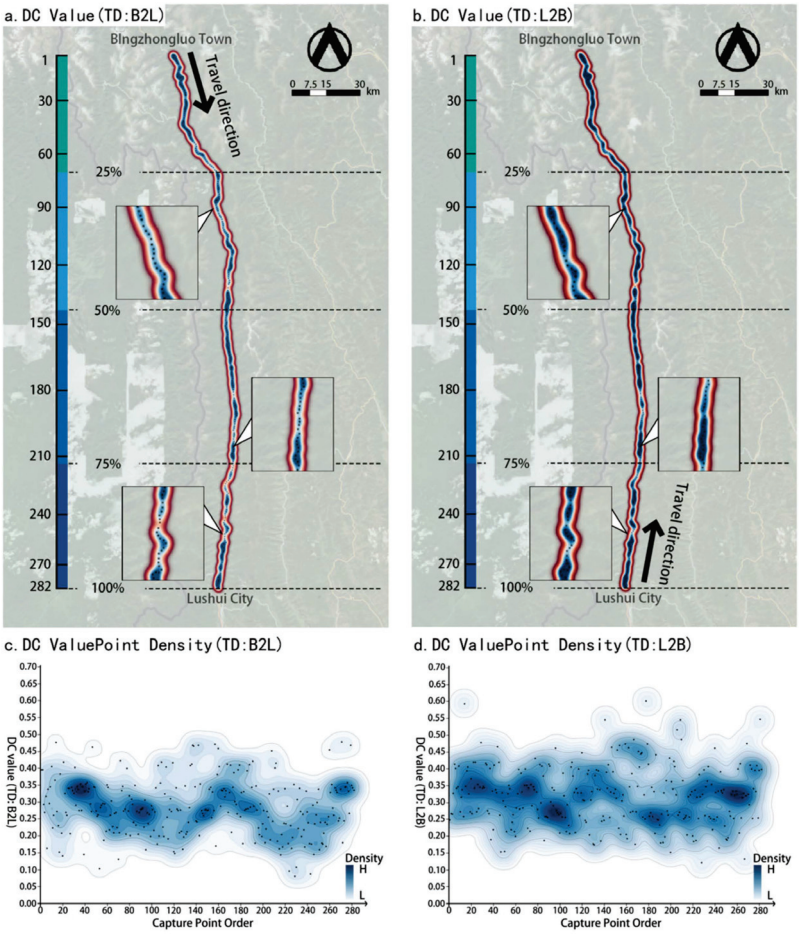


Figure 5. Spatial distribution and density of DC index. (**a**) DC heatmap of B2L direction, (**b**) DC heatmap of L2B direction, (**c**) DC point density of B2L direction, and (**d**) DC point density of L2B direction.

3.4. OD Evaluation

The OD evaluation results (Table 4) indicate that the OD index of the Nujiang Beautiful Road is 0.6407, suggesting a semi-open spatial characteristic. As the road sections are generally wide with lighter traffic, the road occupies an average of 38% of the visual field, while the sky accounts for only 0.2388 and 0.2735, mainly due to the presence of cliffs. Overall, both directions demonstrate a transition from enclosed to open spaces, with sections nearer to Lushui City being more open. However, this shift at the road section level is relatively minor.

While the changes in OD at the road section level may not be substantial, the density map of OD reveals more dispersed points compared to the density maps of NA and DC (Figure 6). This suggests that although the overall OD experience remains stable, local variations may be more pronounced, thereby enhancing the spatial interest of the driving

experience. Furthermore, the difference in OD experience between the two sides of the Nujiang Beautiful Road is more significant compared to differences between sections, with a mean difference of 0.0384. Statistical analysis of OD values using kurtosis reveals that the OD values in the B2L direction are relatively scattered, with a kurtosis of only 2.9108, while the kurtosis in the L2B direction is 4.0425. This indicates that the OD changes in the B2L direction are much more dramatic than those in the L2B direction. This conclusion is also evident in the point density plot. This is because the B2L side is always close to the mountains, and every turn and undulation of the mountain road during the driving process leads to more sensitive OD changes.

Table 4. OD index of Nujiang Beautiful Road.

Road Direction	Min	Max	Mean				
			Total	0–25% Section	25–50% Section	50–75% Section	75–100% Section
B2L	0.5051	0.7616	0.6215	0.6036	0.6176	0.6431	0.6213
L2B	0.4883	0.7700	0.6599	0.6421	0.6437	0.6742	0.6784

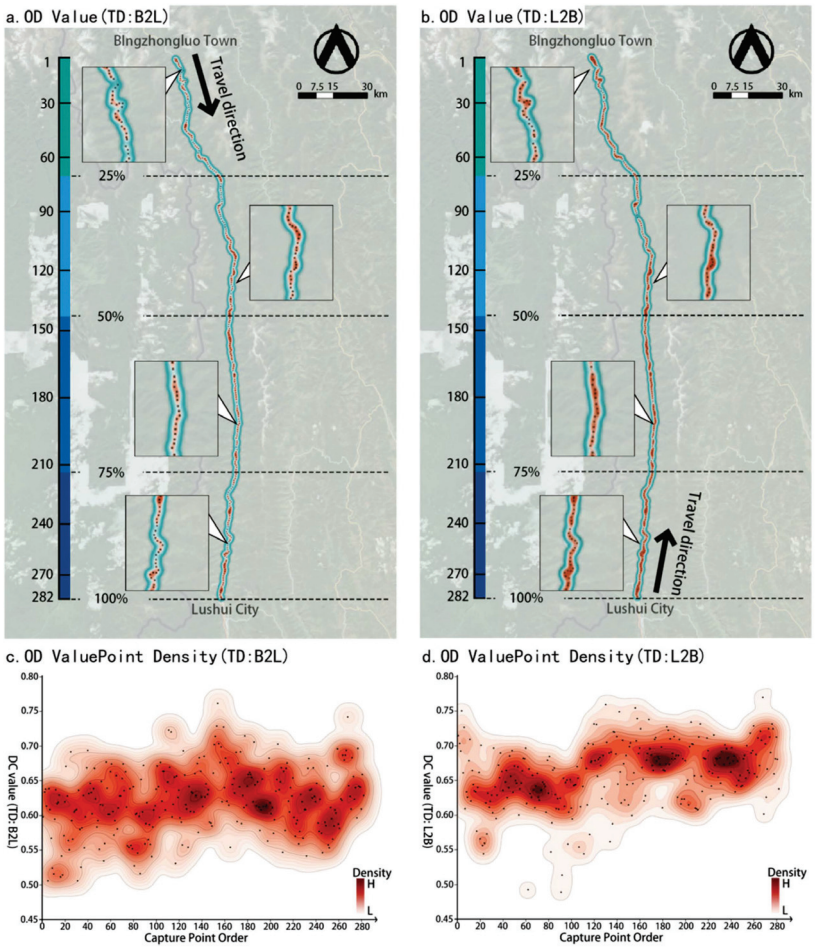


Figure 6. Spatial distribution and density of OD index. (**a**) OD heatmap of B2L direction, (**b**) OD heatmap of L2B direction, (**c**) OD point density of B2L direction, and (**d**) OD point density of L2B direction.

3.5. Characteristics of Extreme Value

Observing the landscape element characteristics at the extremum points of three indicators (Figure 7), the following observations can be made:

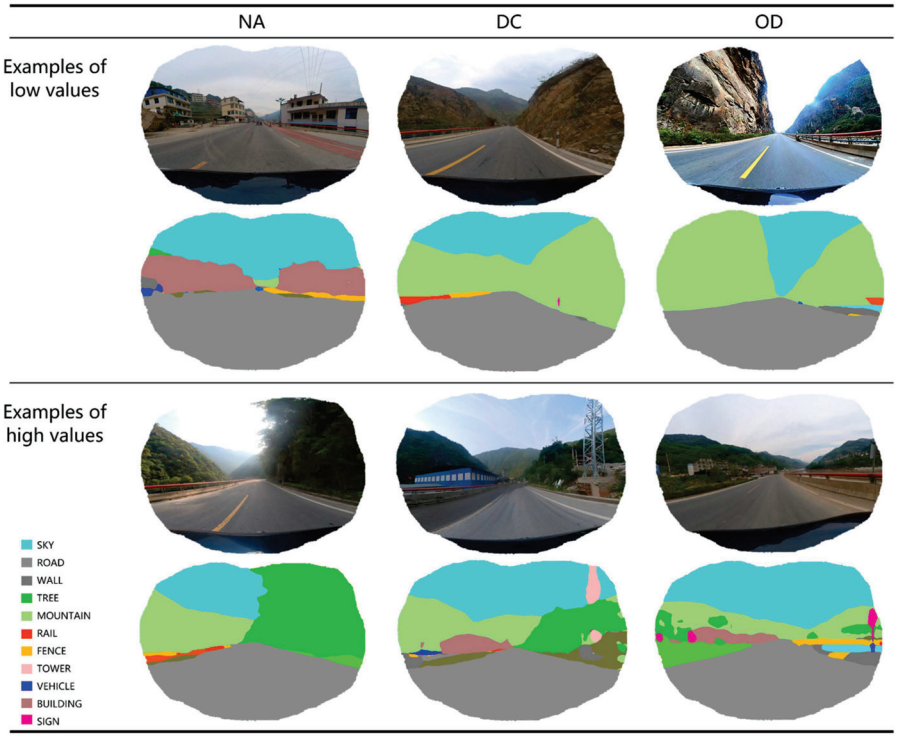


Figure 7. Extreme points of the three indexes in this case study.

The NA value serves as an indicator of the landscape matrix. The highest NA value corresponds to the natural landscape matrix, namely the mountain gorge and forest landscape, while the lowest NA value corresponds to the artificial landscape matrix, namely, the settlement landscape. It is important to note that the settlements are essential for sustaining life. If designed thoughtfully, they can also contribute to the cultural landscape. However, the buildings along the Nujiang Beautiful Road are relatively large in scale and do not harmonize well with the surrounding scenery, appearing somewhat incongruous, thus creating a disconnection between the two types of landscape bases. Nevertheless, these structures are primarily apartment buildings constructed to support poverty alleviation efforts, with the larger scale aimed at accommodating more residents, albeit at the expense of aesthetics. It is believed that after the Beautiful Road boosts the regional tourism economy, the appearance will be improved.

Low DC values indicate shifts in landscape themes. Landscape thematicity necessitates a limited number of landscape elements in the field of view. Earlier, we mentioned the concept of "key visual stimulus factors", which are typically artificial elements. However, this does not imply synchronous changes between DC and NA values. In environments with very low NA values, the DC value may also be low due to the scarcity of natural elements. Along the Nujiang Beautiful Road, low DC values are often manifested in transition zones between urban settlements and natural wilderness, where both natural and artificial elements coexist, resulting in a lack of dominance and a more disorderly appearance. As a validation, among the 144 points (over one-fourth of the total) along the Nujiang Beautiful Road that passed through villages, the road section with more village crossings (25–50%) exhibited a DC standard deviation of 0.0901, while the road section with fewer village crossings (0–25%) had a DC standard deviation of 0.0789. Although this validation method is relatively simplistic, it demonstrates that transitions between natural and artificial themes contribute to fluctuations in the DC value.

Mountains are the key factor influencing the OD value. Since the road area remains relatively constant, the size of the sky area directly reflects the magnitude of the OD value. Upon observing images with the highest and lowest OD values, it becomes evident that scenes with high OD index values feature horizons close to the horizontal line, while scenes

with low OD values exhibit sky shapes resembling a "funnel". Among the landscape elements on both sides of the road, trees, mountains, and buildings are vertical, making them key landscape elements that obstruct sightlines. Pearson correlation tests between the OD value and the proportions of the above three elements reveal that: (a) There exists a strong negative correlation between mountains on both sides of the Nujiang Beautiful Road and the OD value. (b) In the B2L direction, closer to the mountains, the correlation of mountains is stronger than that of trees, whereas in the L2B direction, farther from the mountains, the negative correlation of trees with OD is more pronounced. (c) Interestingly, on the Nujiang Beautiful Road, buildings show a positive correlation with OD. This is because buildings are often situated in relatively flat areas, and their presence does not contribute to openness but rather results from the absence of mountains (Table 5).

Table 5. Pearson test between OD value and landscape elements.

Road Direction	Tree	Mountain	Building
B2L	−0.361 **	−0.432 **	0.253 *
L2B	−0.676 **	−0.230 *	0.257 *

Note: * $p < 0.05$, ** $p < 0.01$.

3.6. 3D Index Cube: Comprehensive Analysis of SRVLE

Among the three indicators mentioned above, 1 and 0 represent the two extreme values of the semantic differential concept, with 0.5 serving as the dividing point between the two concepts. If we represent this evaluation system with a 3D index cube, the visual landscape quality of the scenic road can be divided into eight octants, each representing a different combination of landscape characteristics: ① Naturalness–Diversity–Openness; ② Naturalness–Diversity–Deepness; ③ Naturalness–Coherence–Openness; ④ Naturalness–Coherence–Deepness; ⑤ Artificiality–Diversity–Openness; ⑥ Artificiality–Diversity–Deepness; ⑦ Artificiality–Coherence–Openness; and⑧Artificiality–Coherence–Openness. By expressing the SRVLE of the case with a 3D index cube, each point accurately expresses the visual quality at this shooting point. This method enables a scientific and intuitive representation of the overall visual landscape quality of the scenic road, which is valuable for formulating relevant planning strategies.

For the Nujiang Beautiful Road case, the visual landscape quality of this scenic road exhibits the following characteristics (Figure 8):

Overall, the three-dimensional semantic evaluation of the Nujiang Beautiful Road indicates that most scatter points are concentrated in the third octant, with a few scattered points in the fourth quadrant (Naturalness—Coherence—Deepness) and the first quadrant (Naturalness—Diversity—Openness). A small number of shooting points passed through settlements, with NA values ranging between 0.50 and 0.80, while the vast majority of scatter points were concentrated in the 0.80–1.00 range. The OD values were mostly distributed between 0.60 and 0.80, with a few points between 0.45 and 0.60, demonstrating a semi-open characteristic. The DC values were mostly between 0.15 and 0.50, with a few points above 0.50. Overall, the visual landscape characteristics of the Nujiang Beautiful Road are relatively rich, with a dominant emphasis on naturalness, coherence, and openness, while some sections exhibit relatively deep and diverse landscapes.

Regarding road sections, the disparities in landscape semantic scatter distribution along the Nujiang Beautiful Road are not substantial. Comparatively, the landscape characteristics of the initial and final sections of the road are deeper and more cohesive, while those of the middle sections are opposite. This is primarily because the middle sections traverse Fugong County and Gongshan County, where the surrounding villages near the county towns are relatively dense. Nonetheless, the scatter points are relatively dispersed regardless of whether they are located in the starting, ending, or middle sections of the road. Overall, the continuity of the road landscape along the Nujiang Beautiful Road is not particularly strong, and the roadside landscape is affected by settlements, resulting in a fragmented road landscape.

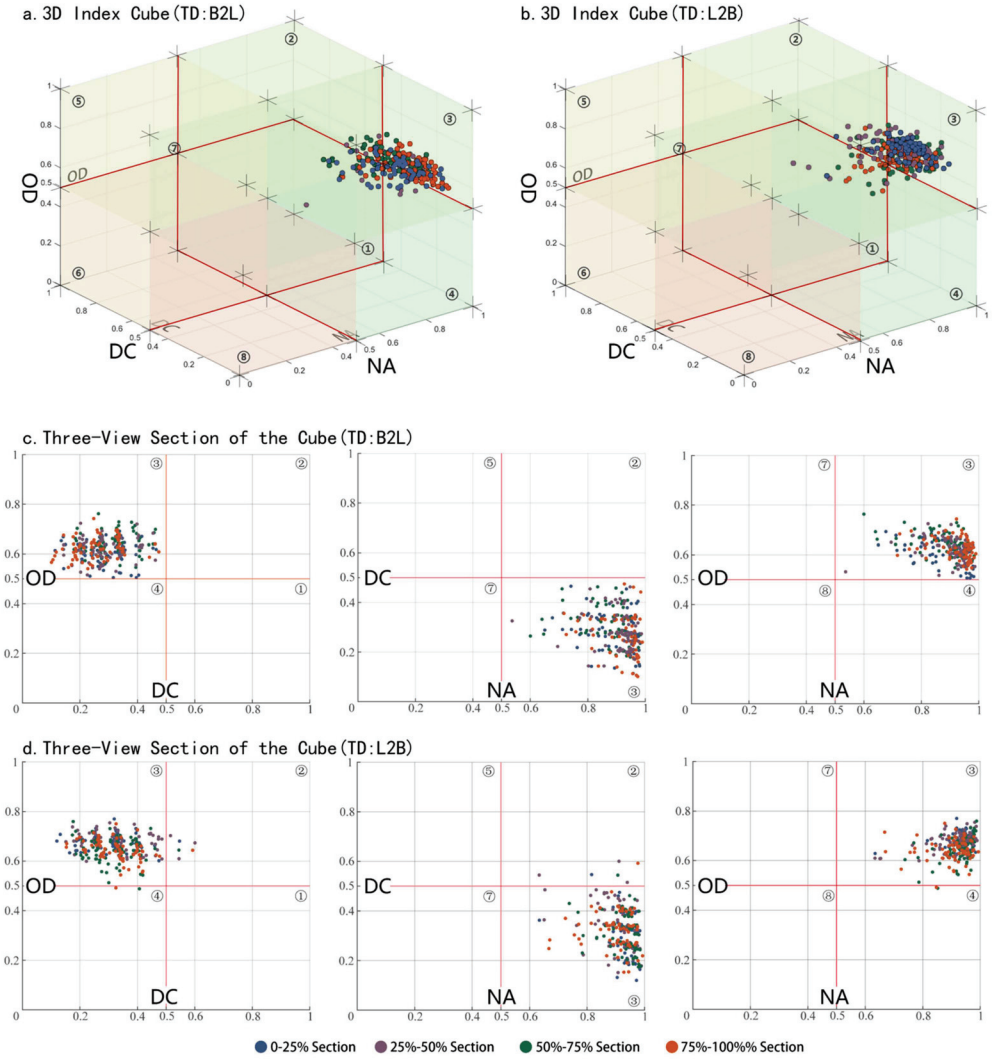


Figure 8. Three-dimensional index cube. (**a**) Three-dimensional index cube for the B2L direction, (**b**) 3D index cube for the L2B direction, (**c**) three-view section of the cube for the B2L direction, and (**d**) three-view section of the cube for the L2B direction.

When comparing the two driving directions, the scatter points on the B2L side are more clustered, exhibiting a narrower range of fluctuations in the three indicators and fewer changes in the visual landscape. Conversely, the scatter points on the L2B side are relatively dispersed, with the minimum value of the OD indicator and the maximum values of the three indicators all distributed on this side, indicating a higher level of variability in this direction. Overall, the visual landscape of the L2B direction appears to be more natural, diverse, and open compared to the opposite side.

4. Discussion

4.1. Contributions of in Practice

In Western countries where scenic road construction began earlier, relevant laws and regulations already include landscape quality considerations within their management scope. However, achieving a balance between humanistic values and objective standards has always been a challenge. The new method proposed in this study solves this problem to a certain extent.

At the landscape design level, the new method offers a human-scale perspective on road landscape characteristics, enabling the development of more comprehensive and detailed design strategies. Examples include the following: (a) Determining ecological

restoration sites: The Nujiang Beautiful Road, being a mountainous scenic road, is vulnerable to soil erosion. Among our 560 visual field images, 123 identified the "bare soil" element, highlighting the significance of fine-grained visual field evaluation for identifying small-scale ecological damage areas. (b) Selecting viewpoint locations: Indicators can pinpoint high- or low-quality landscapes. Locations with high NA and OD values may be suitable for viewpoints. (c) Managing landscape changes: Intense OD value changes along the Nujiang Beautiful Road suggest uncontrolled spatial changes due to natural road vegetation and lack of management, resulting in irregular spatial shifts and abrupt changes that may unsettle drivers [70]. Therefore, employing vegetation to create open and enclosed spaces is essential. (d) Creating segmented themes: Dividing road landscape themes into sections, akin to characteristic zones in scenic areas, enriches and deepens the overall road theme without diminishing its character. (e) Differentiated creation of landscape in both directions: The Nujiang Beautiful Road is situated on the west side of the Nujiang River, causing the B2L direction to be close to the mountains throughout and lacking a view of the water body, resulting in a more oppressive driving experience. Using bridges and roads to connect the opposite side of the canyon could interchange landscape features between directions in specific sections, enhancing the overall landscape experience and offering a comprehensive portrayal of the Nujiang Canyon's landscape characteristics.

At the environmental management level, scenic road management agencies can utilize this method to conduct statistical analysis of the overall level of road visual landscape quality. They can accurately identify road sections requiring targeted rectification measures based on data's high, low, and abnormal values. Additionally, by implementing regular image collection and analysis, management agencies can achieve dynamic monitoring of scenic road visual landscape quality. This enables evaluation of road landscape conservation effectiveness and assessment of whether expected planning goals have been met.

4.2. Scale Effect of Bidirectional Differences

This study examines the binocular visual field of leisure driving and concludes that landscape differences exist between the two driving directions, B2L and L2B. This suggests that previous methods, such as remote sensing data analysis of land cover and DEM, may have overlooked potential differences in visual landscapes between different driving directions. Previous research indicates that results obtained at finer scales may differ from or even contradict those at larger scales [82]. The study finds that while the three indices for both directions exhibit certain differences, they generally follow similar trends. Therefore, these differences may be obscured at larger scales, resulting in consistent performance. To verify this, we conducted a difference test on data from both driving directions to determine whether they exhibit statistically significant differences. Paired t-tests were performed on indicator values (means) from one, three, five, seven, and ten sampling points (Supplementary Materials Table S1). Except for the OD indicator, changes in p-values for NA and DC indicators generally show an increasing trend as the observation scale expands. This suggests that visual landscape differences between B2L and L2B directions gradually weaken and become nonsignificant. This is because the NA and DC indicators are calculated based on the types and quantities of landscape elements, and the landscape pattern that the two-way roads depend on constrains the range of changes in the two-way roads; therefore, these two indicators maintain consistency in the overall characteristics of the visual landscape of the two-way roads. However, the OD values of the two directions of the Nujiang Beautiful Road did not tend to be consistent at a larger scale, because the B2L side of the road is always closer to the mountains; therefore, the difference in OD values between the two sides remains significant.

4.3. Limitations and Prospects

Despite integrating binocular visual physiology and image segmentation technology to ensure both subjectivity and objectivity in assessing scenic road visual landscape quality,

the new method has several limitations that offer insights for future research: (a) While effective for evaluating and managing landscape visual quality on both sides of the scenic road, current image segmentation algorithms are limited to the intuitive perception of the human eye. They cannot reflect a deeper understanding of the landscape by the observer, thus failing to reveal the historical and cultural value behind the visual landscape. For instance, the Nujiang Beautiful Road, surrounded by multiple ethnic minorities, features traditional architecture reflecting unique cultural values that are not captured in the evaluation. (b) The viewer's perspective may change during leisure driving on the scenic road. Although this study simulates the binocular visual field range assuming a normal driving scenario where the driver looks ahead, it overlooks consideration of the subject's dynamic visual field, necessitating exploration of appropriate methods.

While this study demonstrates the effectiveness of our method through the case of the Nujiang Beautiful Road, we acknowledge the limitation of relying on a single case study. Future research should extend the application of this method to a broader range of scenic roads, including those in diverse geographical settings (e.g., coastal and prairie) and with varying levels of development and management. Such an expanded application would not only validate the method's versatility but also potentially uncover how different landscape types influence visual quality indicators. These findings could provide valuable insights for tailoring scenic road planning and management strategies to specific landscape contexts. Although the NA, DC, and OD indicators proposed in this study are universally applicable, they have not been weighted and aggregated to derive a composite score. However, determining weights for specific scenic roads is still of significant importance for evaluating their overall landscape quality. Therefore, future research may consider encouraging scenic road management authorities to develop more refined indicators tailored to specific scenic roads. By integrating the opinions of experts from various fields, the perspectives of local residents, and feedback from motorists, a comprehensive evaluation system can be constructed, leading to more scientifically grounded composite evaluation results. With the advent of the AI era, cross-modal technology may enable image analysis to incorporate cultural significance. Consequently, the visual landscape quality evaluation of scenic roads will evolve towards a more comprehensive, precise, and people-oriented approach, providing better support for the planning, construction, and management of scenic roads and surrounding landscapes.

5. Conclusions

The visual landscape of roads plays a dual role as a foundational resource for scenic road construction and a vital reference for establishing scenic road route systems and integrating transportation and tourism development. To assess the visual landscape resources provided by scenic roads more scientifically and accurately, this paper proposes a new method for measuring the visual landscape quality of scenic roads, exemplified by the Nujiang Beautiful Road in Yunnan. This study tackles both subjectivity and objectivity concerns by leveraging binocular visual field images and image segmentation, achieving SRVLE based on a "non-scale semantic differential approach". Compared to existing methods, this study effectively integrates the strengths of both public and expert evaluation paradigms while mitigating their respective weaknesses. For the public paradigm, we achieve the following: (a) we enhance subjectivity by simulating the binocular visual field; (b) we eliminate the subjectivity and bias associated with questionnaires and scales. For the expert paradigm, we achieve the following: (a) we maintain spatial analysis and precise measurement, exploring landscape quality's spatial distribution objectively; (b) we quantify drivers' visual experiences, addressing the expert paradigm's focus on land attributes and ignoring human perception. This study validates the effectiveness of the new method based on empirical cases, offering a new approach for evaluating the visual landscape quality of scenic roads.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13091381/s1.

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Leveraging Greenspace to Manage Urban Flooding: An Investigation of Nature-Based Solutions Implementation in U.S. Public Parks

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Abstract: Many cities are looking to adopt nature-based solutions (NBS) in greenspace to manage urban flooding and provide diverse co-benefits. Yet little research exists to inform the planning and design of park NBS. This study investigated NBS adoption in 58 public parks across major U.S. cities, using a 2022 survey by the Trust for Public Lands and other secondary datasets. We developed a typology to conceptualize a wide range of park NBS into five high-level categories by size/capacity, location of the gray–green spectrum, and design objectives. We then employed this typology to explore how a park's adopted NBS types may relate to its landscape and sociodemographic contexts. We found that the most used type of NBS in the studied parks was ECO (a typology we defined as conserving, restoring, or creating ecosystems to mitigate flooding through ecological processes and functions), while the least used NBS type was ENG (a typology we defined as imitating natural infiltration processes but having no living elements). Further, parks that adopted ECO had significantly higher percentages of greenspace in the surrounding, as well as higher flood risks. We also found notable—though not statistically significant—evidence of potential associations between the type of NBS implementation in a park and its nearby neighborhoods' income level, poverty, and population racial and age compositions. Moreover, our findings indicated that park visitors were more privileged compared to residents living near a park. We concluded that park contextual factors deserve more explicit consideration in the planning and design of NBS and discussed key implications of this study for practice and future research around park NBS for urban flooding.

Keywords: stormwater management; green stormwater infrastructure; parks; landscape architecture; landscape design and planning; urban greenspace; park equity; living shorelines; stream restoration

1. Introduction

1.1. Parks, Nature-Based Solutions, and Urban Flood Management

Parks are long considered a critical place for city dwellers to experience and interact with nature. A growing body of research indicates that parks can provide various environmental and social benefits, including reducing urban heat island effects, treating stormwater and mitigating flooding, supporting biodiversity, creating opportunities for aesthetic appreciation and recreation, and improving physical, mental, and social health [1–6]. Given these benefits, parks have been identified as playing significant roles for urban sustainability and resilience [7–9]. At the same time, parks are also a key community asset that needs to be sustained amidst adverse climate change impacts such as flooding [10,11]. For example, after Hurricane Sandy, the New York City Parks developed a design and planning guideline for resilient waterfront parks in the city, discussing how parks can offer high-quality experiences while simultaneously possessing the ability to stand and recover quickly from small and large storms [12].

Urban flooding occurs when an excessive inflow of stormwater—which comes from heavy rainfalls or from coastal storm surge and high tides—fails to be infiltrated or carried away by drainage systems in a timely manner [13]. Due to climate change, urban development, and aging water infrastructure, many cities are challenged by more frequent and extreme flooding events and suffer from considerable direct (e.g., buildings, infrastructure, life, and properties) and indirect damages (e.g., detriments to public health and cohesion of community or disruptions of jobs and transportation) [14–17]. Improving the ability of urban communities to withstand, adapt to, and recover from the impacts of flooding has become a major socioeconomic and environmental concern for national, state, and local governments [13].

Nature-based solutions (NBS) have great potential for enhancing urban flood resilience. NBS broadly refers to planning, design, environmental management, and engineering practices that mimic, integrate, and enhance living systems to address societal challenges such as climate change [18–21]. In the context of urban flood management, related terms green infrastructure and green stormwater infrastructure (GI/GSI) have been widely used in the U.S., with a focus on nature-inspired engineering techniques that manage stormwater runoff [22]. In this study, we use the term "NBS" because of its inclusion of more diverse types of practices and its emphasis on adapting to climate change impacts such as urban flooding that is limited to the source of stormwater. Specifically, we consider a rich portfolio of NBS practices ranging from restored or created ecosystems (e.g., flood plains or shorelines) to hybrid measures that integrate natural and engineered elements (e.g., retention ponds or rain gardens) and engineered structures that mimic natural water cycling (e.g., pervious pavement and underground water tanks) that can be used to manage urban flooding [23–25]. Unlike conventional infrastructure that resists and removes water as best as possible, NBS are designed to hold water and accommodate temporary inundation to protect more vulnerable built areas. This can help cities better withstand storms and more quickly recover from extreme events, thus enhancing the flood resilience [26–28]. Furthermore, NBS can provide co-benefits such as improving water quality, supporting biodiversity, and offering opportunities for recreation, aesthetic appreciation, and environmental education [29,30].

Guidelines for introducing NBS in park development and renovation projects to manage urban flooding and provide co-benefits have been developed by many national and municipal agencies in the U.S., such as the Environment Protection Agency (EPA), the National Recreation and Park Association (NRPA), the American Planning Association (APA), the Detroit Water and Sewerage Department, and the Chicago Metropolitan Agency for Planning [31–35]. As these guidelines indicate, the adoption of NBS can enhance park functions beyond aesthetic and recreational uses to improve neighborhoods, which helps to leverage funding and secure parks as protected lands against urbanization [32,35]. This is particularly valuable to underserved communities that have less access to high-quality green amenities but are disproportionately affected by climate change impacts including urban flooding [31,32,34]. In addition, parks often have sizable lands and plants and soils in place that are suitable for adopting NBS practices, particularly practices like detention basins and constructed wetlands that require relatively large areas to function [24,31]. Public spaces like parks also play a critical role in promoting NBS by offering real-life experiences to residents, businesses, and local governments where they can see and feel the benefits [36,37]. Pleasant experiences and positive perceptions of NBS can greatly benefit wellbeing [38] and encourage public acceptance and support for NBS [39].

However, despite much interest in implementing NBS in parks for flood resilience in practice, little research exists to inform planning and design decisions. Tong et al. (2022) examined how NBS implementation has been combined with park facilities (e.g., pathways, playgrounds, and lawns) and outdoor activities in 23 Sponge City parks in Shanghai, suggesting that larger parks can employ a wider range of NBS practices without compromising park recreational services [40]. Feldman et al. (2019) estimated the effectiveness of a park rain garden to manage an adjacent street's runoff and observed an average retention rate of

78% across 26 storms and a full retention for storms under 10 mm [41]. They concluded that parks are an untapped opportunity to manage stormwater and would significantly contribute to municipal stormwater management goals by implementing NBS practices like rain gardens. These previous studies highlight the importance of integrating NBS into parks to achieve environmental and social co-benefits; however, they focused mainly on the techniques and feasibility of NBS implementation, offering limited insights into the planning and design rationale that guides the choice of a park to introduce NBS as well as the specific practice to use.

1.2. Study Objective

This study aims to establish a better understanding of the status of NBS implementation in U.S. parks and how implementing NBS in a park may relate to its broader environmental and social contexts. A growing body of literature has researched how contextual factors can affect NBS's benefits for local communities and identified important landscape and sociodemographic characteristics that should inform the planning and design of NBS at the city and neighborhood scales (e.g., [42–45]). For example, evaluating the multifunctionality of green infrastructure in Detroit, USA, Meerow and Newell (2019) found that GI measures can effectively provide co-benefits if they are sited in response to environmental and social contexts, even though the locations of current GI measures seemed to lack a basis on holistic considerations about these contexts [43]. To contribute to more systematic approaches to NBS implementation in urban parks, this study addressed the following questions: (1) What types of NBS practices have been implemented in parks to manage urban flooding? (2) How does a park's implementation of NBS relate to its surrounding landscapes? Are there associations between a park's landscape contexts and the type of NBS being used? (3) How does a park's implementation of NBS relate to the sociodemographic characteristics of its users? Are there associations between a park's sociodemographic contexts and the type of NBS being used? Our goal is to provide exploratory new insights by investigating some self-reported real-world NBS examples in specific parks, and not to provide a comprehensive examination.

2. Materials and Methods

2.1. Study Sample

We used the 2022 City Park Fact Survey by the Trust for Public Land to obtain parks that constituted the study sample. The Trust for Public Land is a U.S. nonprofit working to protect and create outdoor spaces for all. Since 2012, the organization has surveyed the 100 most populous U.S. cities every year to generate a comprehensive rating, the ParkScore index, for a city's publicly accessible parks, trails, and open space [46]. This data source is used in many studies to examine various aspects of U.S. public parks such as public health outcomes [47] and greenspace equity [48]. The 2022 City Park Fact Survey, for the first time, included a section to inquire park and recreation agencies about examples of practices for building climate resilience that are employed within their park systems [49]. Specifically, five climate change impacts were considered: urban heat, stormwater flooding, coastal or riverine flooding, carbon emissions, and wildfire. This online survey was open from October 2021 to February 2022 [50]. We acquired the publicly available survey results from the Public Tableau (https://public.tableau.com/app/profile/will.klein/viz/ParksasCriticalClimateInfrastructure/Examples, accessed on 15 November 2022). In total, park and recreation agencies in 85 cities across 35 states reported 472 climate resilience-building practices that were implemented in parks and other public recreation facilities and greenspaces, and many of these examples were NBS practices [50].

The survey results dataset was organized by reported examples of climate resilience-building practices, with each row containing five types of descriptive text entries: (1) an overview, a category, and some additional information about the practice; (2) the name of the park where the practice was implemented; (3) the location of the practice (including geographical coordinates, city, and state); (4) the name of the agency that reported the

practice to the survey; and (5) the type of climate change impact the practice aimed to address. For example, one practice included in the survey was using parks as a floodplain in Ann Morrison Park, Boise, ID. The entry for overview was "At Ann Morrison Park, Boise Parks and Recreation is reducing impacts from flooding through using parks as a floodplain"; the entry for additional information was "designed to accommodate seasonal river flooding"; the entry for category was "floodplain"; the entry for agency name was "Boise Parks and Recreation"; and the entry for climate change impact entry was "Flooding—Coastal/Riverine".

Based on the survey data and our study objective, we conducted a systematic screening that involved three stages, each using clearly defined criteria to exclude irrelevant examples of climate resilience-building practices in the original dataset and to compile a sample of parks with NBS adoption for urban flood management (Figure 1).

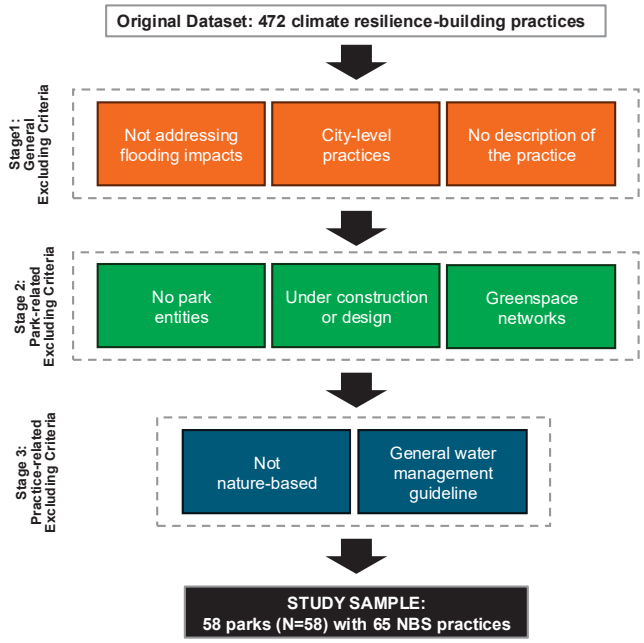


Figure 1. A three-stage systematic screening process involving general, park-related, and practice-related criteria was conducted to determine whether a climate resilience-building practice from the 2022 City Park Fact Survey should be included in this study as one of the park NBS for managing urban flooding. The final study sample consisted of 59 parks and 65 NBS practices (multiple NBS practices were reported in a few parks).

In Stage 1, we first removed 270 examples of climate resilience-building practices from the survey that were not aimed at reducing stormwater or coastal/riverine flooding impacts. Second, we excluded 44 practices that were noted to be applied city-wide (the entry for park name of these practices was "city-wide"), rather than in a specific park. Third, we excluded 29 examples for which the overview entry did not contain any description about what practice was implemented. In Stage 2, we cross-validated a park's name and location with Google Maps, as well as its adopted practices for reducing flooding impacts with the information on official websites (including those run by the park, the corresponding park and recreation department, or/and the associated landscape architecture design firm). We then excluded practices for urban flood management that met any of the following three criteria: (1) the practice was not located in an urban park but in entities such as golf courses, natural trails, nature reserves, and wildlife refuges; (2) the practice was reported for a park that was under construction, renovation, or planning and design when the survey was being conducted; or (3) the practice was from a greenspace network containing many parks. In Stage 3, we further excluded practices that are not nature-based (e.g., seawalls or levees) or involve general water management guidelines rather than specific NBS practices (e.g.,

minimizing grading during construction, recycling water for irrigation, or using native plants). The final study sample included 58 parks across the U.S., with a total of 65 NBS practices (Figure 2).

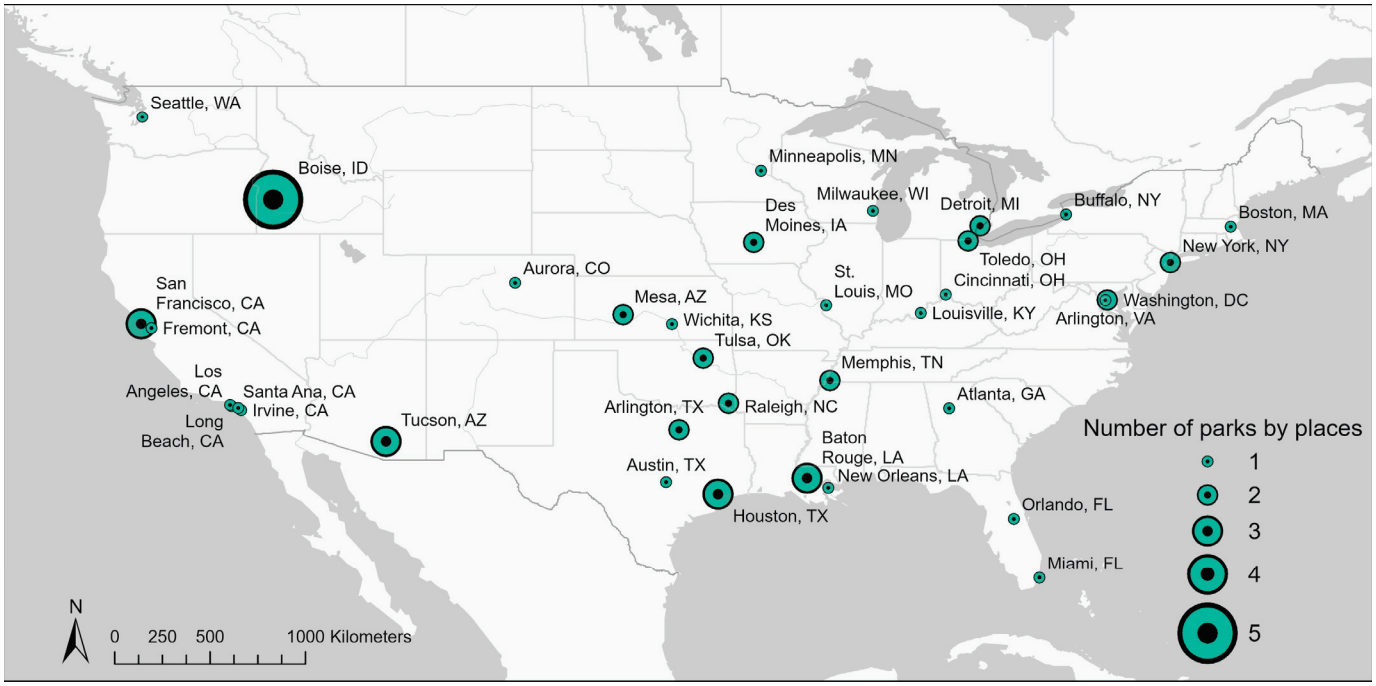


Figure 2. The distribution map of studied parks (N = 58) in 36 U.S. major cities.

2.2. Variables for Landscape and Sociodemographic Contexts

We used secondary data to obtain variables for landscape and sociodemographic contexts. Variables were selected based on the existing literature as well as data availability from various sources. Table 1 lists the description and data source of each variable. All spatial data were processed in ArcGIS Pro 3.2.1.

Previous studies on the development of NBS at the city and neighborhood scales for urban flood management have highlighted landscape contextual factors, including the percentage of land covered by impervious surfaces and greenspace [42,43,51], and flood zones [42], and distance to waterways [45]. We used a 0.5-mile radius, a threshold for walking distance from a park [52,53], when examining the landscape contextual factors. We also examined flood risks within park boundaries. In addition, we included two variables for park characteristics that might also affect the implementation of NBS: park size, which was shown to be positively related to implementations of more diverse stormwater management practices [40]; and distance to the city center, which was shown to drive the abundance of water-sensitive urban design practices and is positively associated with larger practice sizes [45].

For sociodemographic contexts, we used measures from the 2016–2020 American Community Survey 5-Year Estimates at the level of census block groups (CBGs) as proxies. A CBG is a geographic unit that typically has 600 to 3000 residents and constitutes a subdivision of a Census Tract with relatively homogeneous sociodemographic status and living conditions [54]. It is also the smallest geographic entity on which the American Community Survey 5-year Estimates are available. Specifically, we examined variables for race, household income, and poverty, based on the existing literature that considered social justice related to NBS implementation [51,55,56]. We also examined age to account for the elderly and underage populations whose wellbeing can especially benefit from parks, and car availability to account for the ability to access parks.

Table 1. Variables for park landscape and sociodemographic contexts included in this study.

	Name	Description	Data Source
Landscape Contexts	Land cover	Land cover at a 100 m resolution classified as two types: urban vs. vegetated greenspace [%]	Copernicus Global Land Service [57]
	High-flood-risk areas	Flood hazard severity of surrounding and within park areas was regrouped into high and low risks based on FEMA's classification [%] [1]	FEMA Flood Map Service Center [58]
	Distance to waterbody	Euclidean distance from the geometric center of the park to the nearest water body [km]	ESRI USA Parks [59], Copernicus Global Land Service [57]
	Distance to city center	Distance from a park to the city center as measured by the geographic location [km]	ESRI USA Major Cities [60]
	Park size	Area of a park [ha] [2]	ESRI USA Parks [59]
Sociodemographic Contexts	Race	Black, Asian, Hispanic, and White population in a CBG [%]	American Community Survey [61]
	Household income	Median household income (MHI) of a CBG normalized by the average MHI of the city [in USD]	
	Poverty	% of households below the poverty line	
	Age	Age, coded into four groups: under 18 years old, 18–40 years old, 40–65 years old, and over 65 years old.	
	Car availability	Average number of automobiles owned per household	

[1] The high-flood-risk group includes FEMA flood zones that are coded as AE, A, AH, AO, VE, which are all areas with a 1% annual chance of flooding; the low-flood-risk group includes FEMA flood zones that are coded as D or X, which are all other areas considered with low risks or possible but undetermined flood hazards. [2] Park boundary was adjusted manually in ArcGIS when deemed as inaccurate after a visual inspection of each park.

We employed two approaches to identifying the CBGs to focus on. One approach was proximity-based and captures CBGs within a park's 0.5-mile, walking-distance radius. The other is visitation-based and captures the CBGs where the park visitors originate. The proximity-based CBGs (PBC) are easy to identify and represent people living in a park's surrounding neighborhoods. In comparison, the visitation-based CBGs (VBC), though more challenging to identify, represent people visiting the park and are likely to more accurately reflect the sociodemographic characteristics of actual park users.

We obtained information about park visitors' origin CBGs in 2022 from Advan Patterns+, a data product that tracks phone-based mobility for designated points of interest (POIs) [62]. A subset of our studied parks (n = 51) were designated POIs in Advan Patterns. For these 51 parks, we mapped the CBGs from where park visitors had traveled, which are also known as the "catchment" that represents the geographic scope of a POI's visitors. In addition, we also explored the visitation patterns of parks in the subsample (n = 51). We considered three visitation variables available in the Advan mobility data: (a) the average weekly visitation counts of a park; (b) the average ratio of weekly visitation counts to the number of individual visitors, which gauges the frequency of repeated visits to a park; and (c) the median dwell time, which measures the average time visitors spend at a park.

2.3. Data Analysis

2.3.1. NBS Typology

To address our first research question about what types of NBS are implemented in parks to manage urban flooding, we examined descriptions of NBS practices from the survey and identified high-level categories. To achieve this, we first recorded key words in the overview and additional information describing each practice (e.g., pervious pavement, or coastline restoration). We then cross-validated the key words through a visual inspection

and interpretation of a park's aerial view on Google Maps, as well as reading through the statements about flood management on the park's official websites. Based on common-themed key words and the existing literature, we categorized the NBS practices into five general types (Figure 3). For example, using only artificial components and no living element to mimic infiltration, ENG are highly "gray" practices that provide few social and ecological benefits beyond flood management and runoff treatment. In contrast, ECO are highly "green" practices that often conserve or restore wetland and floodplain ecosystems, supporting biodiversity while managing flooding. SGSI, TEM, and POND are hybrid practices that consist of both artificial (e.g., overflow structures and outlet pipes) and living elements. They can have varied aesthetic, recreational, and ecological benefits depending on the specific design and management decisions for plants and landforms.

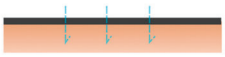
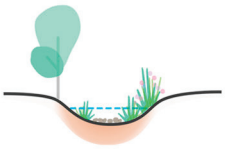
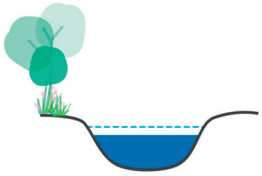
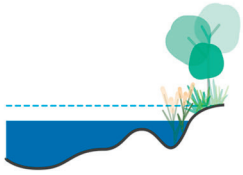
NBS Type		Description	Size/ Capacity	Gray – Green	Design Objectives
	*Engineered Infrastructure (ENG)*	Imitates natural infiltration processes but has no living elements. Examples include pervious pavement and underground water tank.	Small – Medium	Gray	- Reduce flooding - Improve water quality
	*Small-scale Green Stormwater Infrastructure (SGSI)*	Uses specific techniques that employ specially engineered soils and plants to collect and treat storm runoff from nearby impervious surfaces. Examples include rain gardens, bioswales, and bioretention gardens.	Small – Medium	Hybrid	- Reduce flooding - Improve water quality - Enhance aesthetics (often) - Support biodiversity (sometimes)
	*Temporary Landscape-based Water Storage (TEM)*	Holds large amounts of water in wet weather while supports recreation and other activities in dry weather. Examples include detention basins and floodable zones.	Medium - Large	Hybrid	- Reduce flooding - Improve water quality - Recreation (sometimes)
	*Retention Ponds (POND)*	Collects runoff and slowly infiltrates it into the ground. Has perennial water.	Medium - Large	Hybrid	- Reduce flooding - Improve water quality - Enhance aesthetics (often) - Recreation (sometimes)
	*Ecological Design and Management (ECO)*	Conserves, restores, or creates ecosystems to mitigate flooding through ecological processes and functions. Examples include constructed wetlands, restoration of the floodplain of a stream and the marsh and bayou along a shoreline.	Medium - Large	Green	- Flood control - Improve water quality - Enhance biodiversity and ecological health - Recreation (sometimes)

Figure 3. A typology of park NBS for urban flood management, comprehensively defined by size and flood management capacity, location on the gray–green spectrum, and design objectives related to managing urban flooding and other co-benefits [23,24,33,63–65]. The five NBS types are ordered from small to large and gray to green.

2.3.2. Statistical Analysis

Based on the developed typology, we analyzed the associations of the type of NBS practice used in a park and variables for its landscape and sociodemographic contexts to address our research questions about how contextual factors might affect NBS implementation in parks. We first calculated descriptive statistics for the five NBS types and the contextual factors by each type. We then employed one-way ANOVA to further test the statistical significance of the variations in landscape and socioeconomic contextual factors by NBS type. Further, we used the post hoc Tukey–Kramer test to better understand the pattern of pairwise differences among the five NBS types. The Tukey–Kramer test was

chosen given the exploratory nature of this study (i.e., we did not have planned comparisons of certain NBS types based on current knowledge) as well as the unequal sample sizes [66]. Between-group and pairwise differences were considered statistically significant at p-value < 0.05. We also conducted a t-test to compare the distribution of socioeconomical characteristics of PBC and VBC across all parks, accounting for differences between visitors and adjacent residents. Significant differences were determined when p-value < 0.05. All statistical analysis was performed using Microsoft Excel 16.80 and Python 3.12.4, with descriptive statistics conducted in Microsoft Excel and ANOVA as well as the post hoc Tukey–Kramer test conducted using a Python package "Statsmodels" (Ver. 0.14.1) [67].

3. Results

3.1. Implementing NBS in Parks for Urban Flood Management

3.1.1. Park Geographic Scope and Flood Management Focus

The NBS practices in the 58 parks we focused on were reported by park and recreation agencies from 36 cities across 24 states in the U.S. These cities counted for 42.4% of the cities that responded to the survey and 36% of the most 100 populous cities in the U.S. that were invited to take the annual City Park Fact Survey. In addition, nearly half of these cities (n = 15) identified more than one example of parks that had adopted NBS practices. This suggests that the park and recreation agencies in many big cities are leveraging public park space to help manage urban flooding.

Cities that reported a high number of parks with examples of NBS included the following: Boise, ID (five parks); and Baton Rouge, LA, Houston, TX, San Francisco, CA, and Tucson, AZ (three parks each). At the state level, eight parks were in California, followed by Texas (six parks), and Arizona and Idaho (five parks each). Using the region designations in the Fifth National Climate Assessment [68], our study sample had more examples from the Southwest (fourteen parks), Southeast (twelve parks), and Midwest (eleven parks), and fewer examples from the Southern Great Plains (nine parks), the Northwest (six parks), and the Northeast (six parks). No example was reported from the Northern Great Plains (i.e., Montana, South and North Dakota, and Wyoming).

More often, NBS practices were reported for the management of stormwater flooding than for coastal/riverine flooding. Out of the 58 parks in the study sample, 74.1% (n = 43) implemented NBS practices to mitigate impacts from stormwater flooding, while 37.9% (n = 22) implemented NBS practices to mitigate impacts from coastal/riverine flooding; in addition, 12.1% parks (n = 7) used NBS for both flood management focuses.

3.1.2. Types of Park NBS Practices

The study sample presented a wide range of NBS practices for urban flood management (Figure 4 and Supplementary Materials). Based on the NBS typology we developed, overall, ECO were implemented most often in parks, followed by SGSI, POND, TEM, and ENG (Figure 4). Comparing the management focus of stormwater versus coastal/riverine flooding, parks addressing stormwater most often used SGSI, while parks addressing coastal/riverine flooding most often used ECO at a substantially higher rate than other types of practices. ENG were least often used across both management focuses, though it was most often used in parks addressing stormwater and coastal/riverine flooding simultaneously.

Seventeen parks in this study sample (29.3%) had multiple practices, including all seven parks that addressed both stormwater and coastal/riverine flooding. Among the remaining ten parks, seven addressed stormwater flooding and three addressed coastal/riverine flooding. Practice-wise, the five types of NBS were quite evenly used in these parks. TEM was most common, adopted in nine parks and often combined with POND and ECO. The top three combinations included TEM and POND (in five parks), TEM and ECO (in four parks), and ENG and SGSI (in four parks).

NBS Type	Practices
ECO	bayou, riprap and flood-tolerant plants along river, constructed wetland, constructed marshland, native prairie in detention basin, habitat restoration, preserved and restored bayou, preserved and restored marsh, wetland-based park, restored stream channels, shore/coastal restoration, preserved wetland, creek restorations
SGSI	bioswales, bioretention, rain gardens
POND	detention ponds, retention basins, bioretention ponds
TEM	seasonal river flooding accomodation, detention basin
ENG	porous/permeable pavement, underground stormwater tanks, underground retention tanks

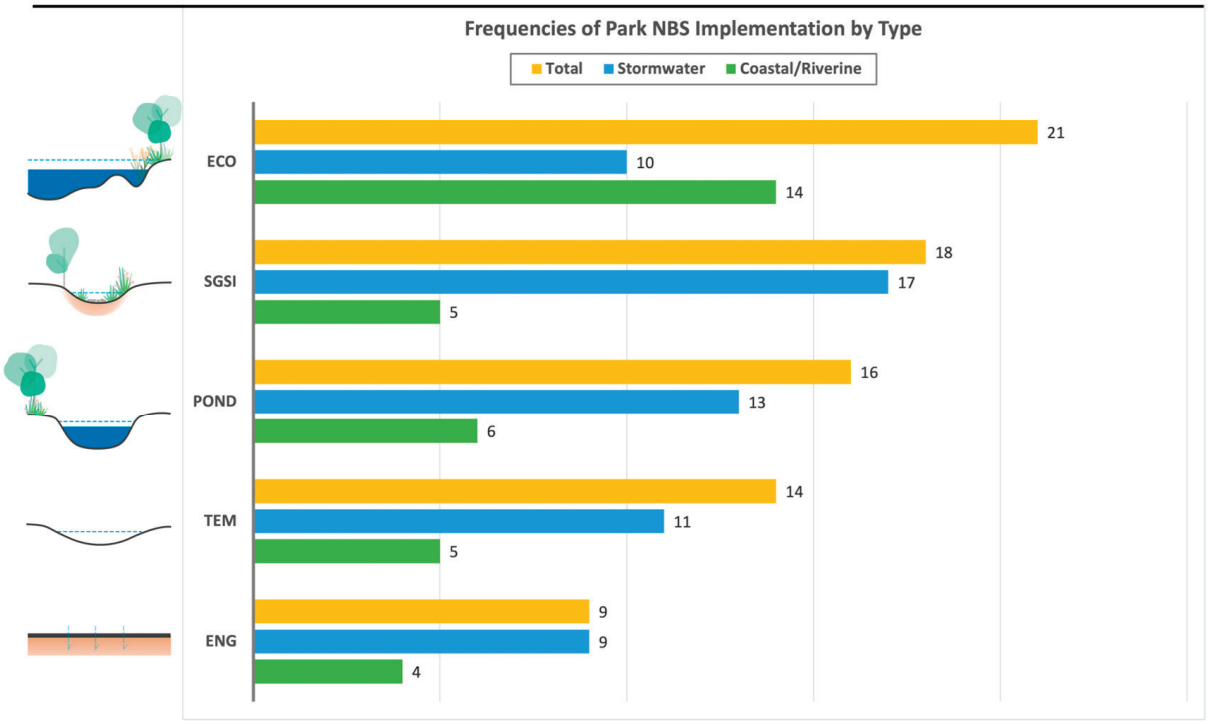


Figure 4. Specific flood management practices implemented in the studied parks, grouped by our typology of NBS, and the frequencies of the five NBS types (ENG: engineered infrastructure; SGSI: small-scale green stormwater infrastructure; TEM: temporary landscape-based water storage; POND: retention ponds; ECO: ecological design and management).

3.2. NBS Implementation and Landscape Contexts

Tables 2 and 3 summarize the descriptive statistics for landscape contextual factors of parks and the ANOVA results, respectively.

Regarding surrounding land cover conditions, parks with SGSI on average had the most coverage of built areas, while parks with ECO had the least coverage of built areas. Parks with ENG on average had the least coverage of greenspace and the most coverage of surface water in their surroundings. In contrast, parks with POND had the most coverage of surrounding greenspace and parks with TEM had the least coverage of surrounding water. Parks with ECO also had relatively high coverage of greenspace in their surroundings. The differences in the surrounding built area and greenspace coverages between parks implementing varied NBS types were statistically significant as indicated by the ANOVA (Table 3). Further, post hoc tests using pairwise comparisons confirmed that parks with SGSI had statistically significant higher coverage of built areas than parks with ECO; and parks with ECO and POND both had statistically significant higher coverage of greenspace than parks with ENG and SGSI (Figure 5).

Table 2. Descriptive statistics (means, with SD in parentheses) of landscape contextual factors of parks (N = 58) by NBS type.

Category	Variable	ECO	SGSI	POND	TEM	ENG
Surrounding land cover	% Greenspace	36.18 (19.54)	15.43 (14.64)	37.94 (25.77)	27.28 (17.58)	12.74 (11.27)
	% Built	50.94 (19.49)	80.62 (17.62)	58.67 (24.87)	70.14 (19.00)	72.98 (18.76)
	% Water	12.88 (20.65)	3.95 (7.14)	3.39 (6.51)	2.58 (9.03)	14.28 (15.13)
Surrounding and within-park flood risks	% High-risk area (surrounding)	33.79 (28.13)	10.09 (13.27)	13.55 (15.93)	11.54 (18.64)	20.81 (20.08)
	% High-risk area (within-park)	44.74 (43.27)	11.17 (21.32)	22.84 (37.19)	21.22 (36.94)	11.57 (17.72)
Park geographic characteristics	Area (ha)	62.03 (80.46)	11.91 (16.42)	43.75 (71.03)	42.47 (70.98)	10.30 (11.15)
	Distance to city center (km)	7.26 (4.99)	4.56 (3.40)	7.37(4.85)	5.38 (3.55)	4.38 (3.93)
	Distance to water bodies (km)	1.79 (2.43)	2.38 (2.40)	3.40 (3.74)	3.63 (3.36)	0.94 (1.57)

Table 3. ANOVA results for landscape contextual factors of parks by NBS type.

Category	Variable	Across NBS Types	
		F-Value	*p*-Value
Surrounding land cover	% Greenspace	5.359	0.001 ***
	% Built	3.405	0.013 *
	% Water	2.446	0.054
Surrounding and within-park flood risks	% High-risk area (surrounding)	4.569	0.002 **
	% High-risk area (within-park)	2.797	0.032 *
Park geographic characteristics	Distance to center	1.734	0.152
	Area	2.189	0.079
	Distance to water body	1.958	0.110

* $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Overall, high-flood-risk areas constituted 24.67% within the park boundaries and 18.83% in the park surroundings across parks in our study sample. Parks with ECO had the highest flood risks on average on both the surrounding and within-park levels. In contrast, parks with SGSI had the lowest surrounding as well as within-park flood risks. In addition, parks with TEM had relatively low surrounding flood risks and ENG had relatively low within-park flood risks. The following ANOVA test shows that the differences in flooding risks between parks implementing varied NBS types were statistically significant for both surrounding and within-park conditions (Table 3). Further, post hoc tests confirmed that parks with ECO had statistically significant higher surrounding flood risks than parks with SGSI, TEM, and POND. They also had statistically significant higher within-park flood risks than parks with SGSI (Figure 5).

None of the associations between park geographic characteristics and the type of NBS implementation was statistically significant, as indicated by the ANOVA.

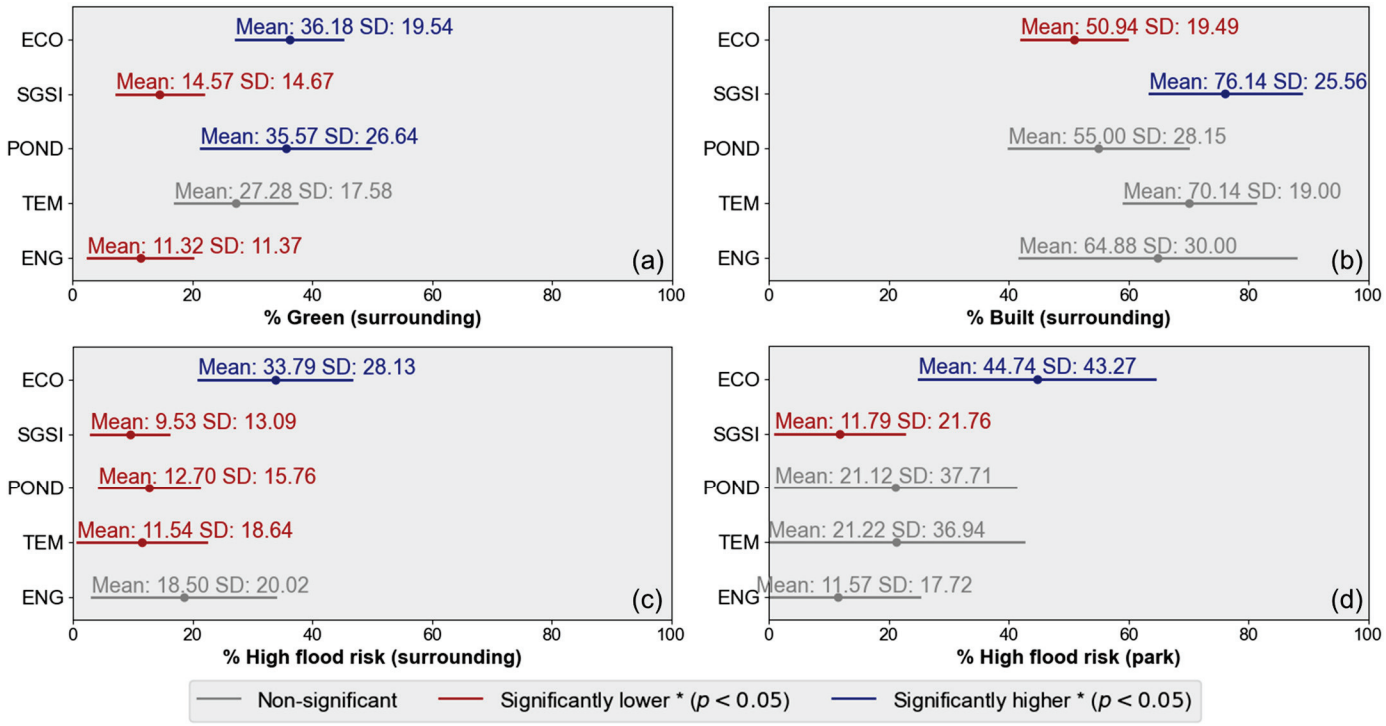


Figure 5. Results from post hoc Tukey–Kramer test for the four landscape contextual variables that showed significant differences among NBS types based on ANOVA. For (**a**) % Green of surrounding area, the difference was mainly explained by the higher percentages around parks with ECO and POND and the lower percentages around parks with ENG and SGSI. For (**b**) % Built of surrounding area, the difference was mainly explained by the lower percentages around parks with ECO and the higher percentages around SGSI. For both (**c**) % High flood risk areas surrounding a park and (**d**) % High flood risk areas within a park, the higher percentages of parks with ECO substantially contributed to the between-group differences. Compared to parks with ECO, parks with SGSI, TEM, and POND had lower percentages of high-flood-risk areas in their surroundings and parks with SGSI had lower percentages of high-flood-risk areas within.

3.3. NBS Implementation and Sociodemographic Contexts (RQ3)

Our analysis of sociodemographic contextual factors involved the following proximity-based and visitation-based CBGs: (1) PBC-N: proximity-based CBGs using the complete study sample (N = 58); (2) VBC-n: visitation-based CBGs using a subset of parks identified as points of interests in the Advan mobility data (n = 51); and (3) PBC-n: proximity-based CBGs using the subset of parks identified as points of interests in the Advan mobility data (n = 51), for comparisons with VBC-n. Table 4 summarizes and compares the descriptive statistics of sociodemographic contextual variables among these three groups.

We then performed an ANOVA to investigate the difference in sociodemographic contexts by park NBS type. The ANOVA results indicated no statistically significant difference in any variable. However, we observed some noteworthy patterns in the descriptive statistics. First, some park NBS types had repeated highest and lowest means of variables in the two proximity-based groups (PBC-N and PBC-n), which provides evidence of potential correlations between the type of NBS adopted in a park and its nearby neighborhoods' sociodemographic status that are worth further research. Second, the proximity-based versus visitation-based sociodemographic contexts showed notable differences in a few sociodemographic contextual variables.

Table 4. Means and standard deviations (in parentheses) of the sociodemographic contextual variables by NBS type. Results are reported to compare three groups: PBC-N (proximity-based CBGs using the study sample, N = 58), PBC-n (proximity-based CBGs using the sample subset with available mobility data, n = 51), and VBC-n (visitation-based CBGs using the same sample subset, n = 51).

	Variable	ECO	SGSI	POND	TEM	ENG
Economic status	MHI (PBC-N)	77,910 (37,127)	79,598 (34,715)	79,484 (31,953)	56,185 (21,548)	99,425 (43,161)
	MHI (PBC-n)	66,341 (31,879)	79,454 (32,112)	76,784 (30,118)	72,134 (37,700)	91,177 (48,745)
	MHI (VBC-n)	68,188 (17,294)	80,452 (31,629)	73,081(29,884)	60,340 (10,274)	74,310 (27,035)
	Adjusted MHI [1] (PBC-N)	1.39 (0.74)	1.00 (0.51)	1.24 (0.47)	0.90 (0.39)	1.30 (0.59)
	Adjusted MHI (PBC-n)	1.30 (0.82)	1.07(0.42)	1.17 (0.47)	0.82(0.46)	1.03 (0.32)
	% Poverty (PBC-N)	16.58 (12.47)	19.71 (12.63)	12.33 (10.16)	21.92 (9.89)	17.65 (12.58)
	% Poverty (PBC-n)	19.92 (12.81)	12.61 (12.06)	12.21 (7.72)	21.68 (14.51)	23.10 (16.17)
	% Poverty (VBC-n)	14.06 (6.09)	12.53 (6.54)	13.55 (6.72)	16.56 (4.00)	15.23 (5.71)
Race and ethnicity	% White (PBC-N)	53.12 (25.46)	41.39 (23.66)	63.61 (34.59)	48.99 (25.54)	49.64 (22.98)
	% White (PBC-n)	42.08 (23.89)	64.53 (39.32)	37.65 (28.23)	42.87 (26.05)	47.48 (25.28)
	% White (VBC-n)	67.84 (16.28)	63.01 (21.43)	64.48 (18.06)	60.75 (16.32)	62.02 (13.50)
	% Black (PBC-N)	22.05 (25.47)	23.33 (24.66)	21.03 (28.76)	21.61(22.83)	13.82 (19.57)
	% Black (PBC-n)	30.02 (28.32)	19.13 (30.19)	36.47 (34.22)	26.29 (23.53)	12.56 (14.29)
	% Black (VBC-n)	16.57 (14.50)	15.59 (18.16)	20.82 (20.70)	18.26 (16.39)	13.81 (7.93)
	% Asian (PBC-N)	4.46 (4.60)	16.43 (20.94)	8.51 (16.96)	4.62 (3.97)	21.77 (20.58)
	% Asian (PBC-n)	4.59 (5.17)	11.20 (20.13)	5.71 (6.71)	14.73 (20.34)	29.53 (21.62)
	% Asian (VBC-n)	5.26 (3.33)	11.59 (16.30)	4.75 (2.59)	4.45 (1.81)	11.75 (10.43)
	% Hispanic (PBC-N)	18.89 (25.21)	15.33 (13.24)	12.24 (14.04)	24.55 (26.57)	17.81 (16.19)
	% Hispanic (PBC-n)	20.25 (27.73)	15.46 (16.08)	19.78 (25.18)	11.95 (7.66)	21.30 (14.86)
	% Hispanic (VBC-n)	22.22 (19.28)	16.19 (12.92)	10.89 (6.60)	29.84 (22.99)	18.54 (12.14)
Age	% Senior (65+) (PBC-N)	12.79 (3.74)	10.99 (4.37)	14.23 (6.42)	11.93 (3.58)	12.16 (5.03)
	% Senior (65+) (PBC-n)	11.45 (3.58)	13.33 (7.40)	14.05 (3.05)	9.56 (3.23)	9.64 (4.68)
	% Senior (65+) (VBC-n)	12.34 (1.95)	12.84 (2.21)	12.46 (1.07)	11.60 (1.64)	14.02 (2.61)
	% Under 18 (PBC-N)	21.10 (5.82)	18.88 (9.76)	21.07(6.18)	18.98 (7.85)	17.42 (8.24)
	% Under 18 (PBC-n)	22.20 (6.54)	21.77 (6.97)	19.36 (5.88)	21.37 (11.68)	17.55 (12.37)
	% Under 18 (VBC-n)	24.64 (2.93)	23.01 (3.99)	25.56 (2.17)	25.40 (2.62)	22.84 (2.54)
Car	# Cars/household (PBC-N)	1.56 (0.42)	1.44 (0.45)	1.67 (0.31)	1.47 (0.36)	1.26 (0.57)
	# Cars/household (PBC-n)	1.61 (0.37)	1.73 (0.33)	1.53 (0.70)	1.53 (0.38)	1.26 (0.41)
	# Cars/household (VBC-n)	1.75 (0.30)	1.75 (0.19)	1.79 (0.23)	1.75 (0.17)	1.38 (0.49)

[1] Adjusted MHI was not included for visitation-based CBGs as the origin of visitation sometimes was beyond one city. As a result, the comparison of CBGs-level MHI to city-level MHI was not meaningful.

3.3.1. Park NBS Adoption and Nearby Neighborhoods' Sociodemographic Status

In both PBC-N and PBC-n, regarding economic status, the mean poverty rates were lowest in neighborhoods around parks with POND. In contrast, parks with TEM were in neighborhoods with the highest average poverty rate in PBC-N and the second highest in PBC-n. Similarly, the mean adjusted MHI was lowest in neighborhoods around parks with TEM in both PBC-N and PBC-n, while parks with ECO were in neighborhoods with the highest average adjusted MHI. For race and ethnicity, the mean Asian population percentage was highest in neighborhoods around parks with ENG and lowest in neighborhoods around parks with ECO in both groups. In addition, the mean Asian population percentage varied greatly among parks with different NBS types, ranging from below 5% to nearly 30%. The mean Black population percentages were lowest in neighborhoods around parks with ENG. In contrast, parks' surrounding neighborhood White and Hispanic population percentages showed some opposite trends in PBC-N and PBC-n, suggesting potentially higher variations in White and Hispanic populations in neighborhoods around POND,

SGSI, and TEM. Regarding age and car availability, the mean percentage of seniors was highest in neighborhoods around parks with POND in both PBC-N and PBC-n. In contrast, parks with TEM were in neighborhoods with the lowest mean percentage of seniors in PBC-n and the second lowest in PBC-N. The mean percentage of populations under 18 years old was highest in neighborhoods around parks with ECO in both PBC-N and PBC-n. In addition, parks with ENG were in neighborhoods with the lowest mean percentage of populations under 18 years old and number of cars owned in both groups.

3.3.2. Differences between Proximity- and Visitation-Based Sociodemographic Contexts

Comparing the proximity-based and visitation-based results (PBC-n vs. VBC-n), there are some notable differences between people who visit the parks versus those living close to the parks. First, the mean poverty rates in VBC-n were lower than those in PBC-n across parks with all types of NBS except POND. Second, the mean White population percentages in VBC-n were higher than those in PBC-n across parks with all types of NBS except SGSI. In contrast, the mean Black population percentages in VBC-n were lower than those in PBC-n across parks with all types of NBS except ENG. Third, the mean average number of cars owned per household was higher in VBC-n than in PBC-n across parks with all types of NBS. Fourth, the mean percentages of populations under 18 years old were higher in VBC-n than in PBC-n across parks with all types of NBS and showed a smaller variability by NBS type.

To further investigate the differences between VBC-n and PBC-n, we performed a follow-up *t*-test for % poverty, % White, % Black, average number of cars per household, and % under 18. In summary, the differences in grand means across parks (n = 51) were statistically significant for all five variables but % Black (Table 5). These results might be explained by that wealthier, White populations comprise more users of parks, even when many low-income, Black populations may live close by. In addition, many park users might be families with kids visiting from beyond the 0.5-mile walking distance.

Table 5. T-test results for the grand means across the sample subset with available mobility data (n = 51), comparing between visitation-based CBGs (VBC-n) and proximity-based CBGs (PBC-n). Cohen's d values indicate small (0.2–0.5) and medium (0.5–0.8) effect sizes for the four variables.

Variables	Group	Mean	SD	t-Value	*p*-Value	Cohen's d
% Poverty	Visitation-based Proximity-based	14.28 18.30	5.84 12.62	−2.06	0.043	−0.409
% White	Visitation-based Proximity-based	64.19 48.14	17.05 29.80	3.34	0.001	0.661
# Cars owned per household	Visitation-based Proximity-based	1.71 1.56	0.293 0.435	2.12	0.037	0.420
% Populations under 18 years old	Visitation-based Proximity-based	24.37 20.32	3.07 8.22	3.29	0.002	0.652

3.3.3. Descriptive Results for Park Visitation Patterns by NBS Type

We also examined Advan mobility data-based visitation variables for 51 parks to provide additional insights for visitation patterns of parks with varied types of NBS. On average, these parks served users from a broad geographic scope, ranging from 263 origin CBGs (parks with SGSI) to 538 CBGs (parks with ENG). Interestingly, the median dwell time showed an opposite trend—visitors to parks with ENG on average spent the shortest time (27 min, SD = 8.57) while visitors to parks with SGSI spent the longest time (44 min, SD = 36.24). Given the result that ENG and SGSI were both relatively close to the city center, where CBGs are often smaller and denser, this difference is more likely explained by park design characteristics or park user preferences than the location of the park. In addition, the mean ratios of visits to visitors were very similar across all parks, except a higher ratio for parks with TEM, indicating a possibility of visitors coming repeatedly to these parks.

In contrast, parks with TEM had the lowest weekly visitation on average. These results should be treated as exploratory and demand further investigations since the differences in visitation patterns by park NBS type were not statistically significant, as indicated by the ANOVA.

4. Discussion

4.1. Park NBS and Urban Flood Management

This study showed that a high percentage of park and recreation agencies in U.S. big cities are adopting NBS in public parks to mitigate urban flooding and are explicitly linking this effort with climate resilience and adaptation. The source of urban flooding (e.g., riverine, coastal, stormwater, flash, and snowmelt) varies greatly in different regions and cities, and flood risks depend on many factors including the natural environment, land use history and pattern, and stormwater and sewer systems [13]. We found that nearly 75% of parks in the study sample have implemented NBS practices for managing stormwater-related flooding than coastal/riverine flooding. For example, park and recreation agencies reported many more parks that addressed stormwater-related flooding (fourteen stormwater examples versus one coastal/riverine flooding example out of the fourteen parks) even in the Southwest Region where many coastal urban communities are challenged by increasing flooding events due to extreme rainfall, storm surge, high tides, and sea level rises [68]. The dominant focus on stormwater in the current park NBS adoption might be attributed to the widespread idea of leveraging green stormwater infrastructure (GSI) to meet requirements of the Clean Water Act. Since the 1990s, the Environmental Protection Agency (EPA) has been promoting green infrastructure as a cost-effective approach to reduce non-point source pollution in urban stormwater runoff and improve local water quality [69].

Related to the result that notably more parks use NBS to address stormwater-related flooding, our findings indicated relatively low flood risks within and in the immediate surroundings of parks that have adopted NBS. Overall, high-flood-risk areas constituted only 24.67% within the park boundaries and 18.83% the park surroundings (based on a 0.5-mile radius), with percentages ranging from 11 to 45% and 10 to 34% by the NBS type, respectively. In our study, areas of high flood risk were determined according to the FEMA flood maps. These maps define flood hazard zones by the 100-year flood [49] and do not necessarily include urban areas prone to stormwater-induced flooding [13]. In addition, this study provides evidence of the risk of compound floods, which describes the occurrence of two or more independent events that produce flood hazards jointly in space and/or time [70], and the effort of leveraging park space to address compound flooding through various NBS. A total of 12.1% of parks in our study sample implemented NBS practices for both stormwater and coastal/riverine flooding management. We argue that the future planning, design, and management of urban parks need to pay more attention to coastal, riverine, and compound flooding and further explore how to expand the role of NBS in flood control. For example, some landscape architects are leading innovative planning and design strategies for shoreline parks that integrate protection berms, coastal ecosystem restorations, amenities, and recreational facilities to enhance flood resilience and biodiversity while creating opportunities for people to interact with nature [71,72].

4.2. Park NBS Type, Contextual Factors, and Implications of Their Relationships

Overall, the most used type of NBS in the studied parks was ECO (a typology we defined as conserving, restoring, or creating ecosystems to mitigate flooding through ecological processes and functions), while the least used NBS type was ENG (a typology we defined as imitating natural infiltration processes but having no living elements). This suggests that preserving and enhancing natural landscapes may be an important goal of adopting NBS in parks in the U.S. Some scholars argue that measurable benefits for biodiversity should be a necessity for NBS [73]. Urban parks are well-positioned to adopt NBS practices that can provide more ecological benefits because parks largely consist of

natural landscapes and are already protected from land development. In addition, unlike Tong et al. (2022) [40], we did not find a notable correlation between park size and NBS type or the presence of multiple types of practice. In this study, nearly 30% of the parks adopted multiple types of NBS practices, and we observed a tendency of using multiple types of practices when the flooding management goal addressed both stormwater and coastal/riverine flooding or focused only on stormwater-related flooding.

Importantly, this study provides evidence of some noteworthy associations between the NBS type a park has adopted and its landscape and sociodemographic contexts (Figure 6), suggesting that the choice of NBS might be implicitly influenced by the surrounding environment and communities. Below we discuss key findings on the relationships between park NBS type and contextual factors and their implications.

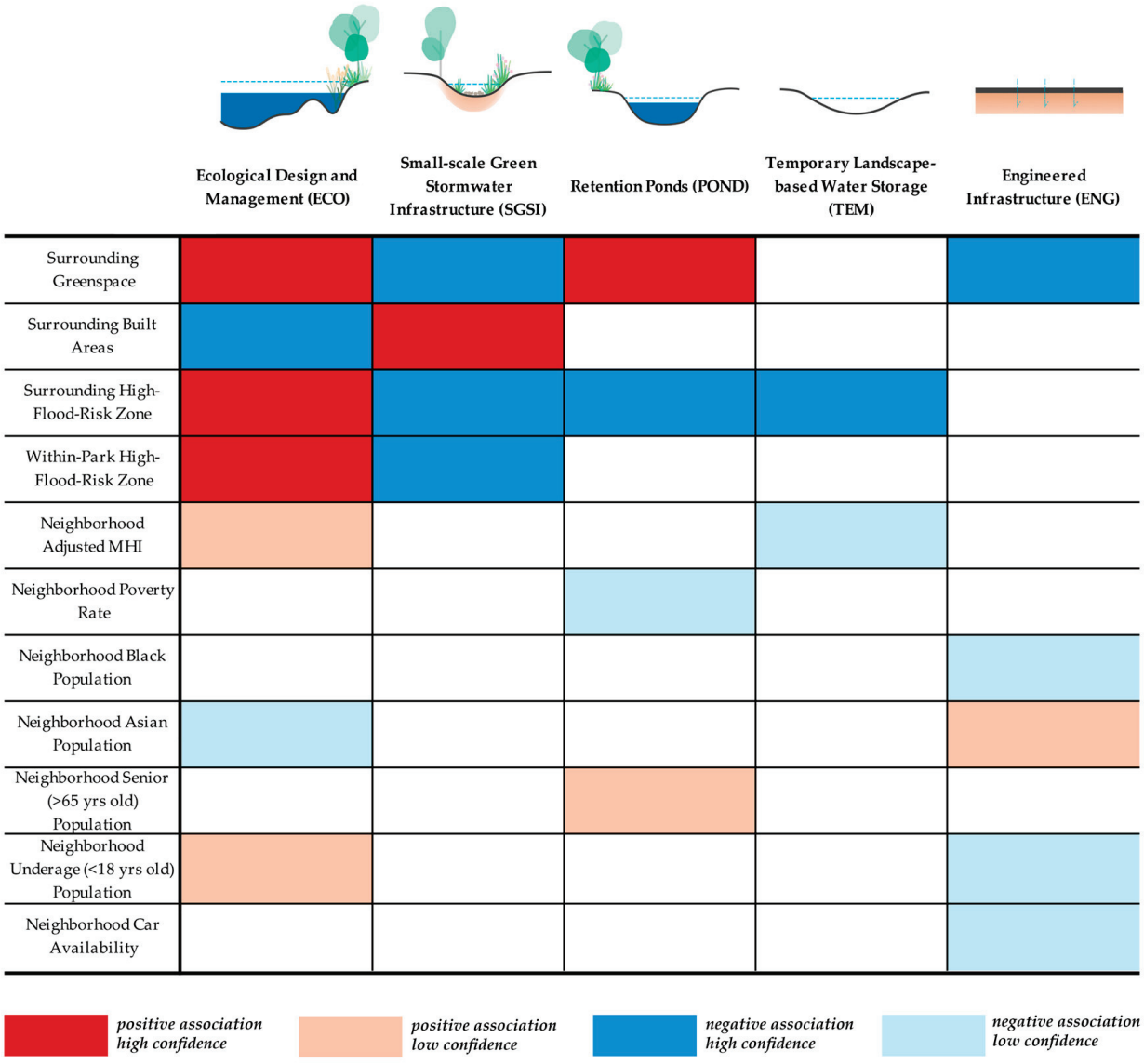


Figure 6. A visual summary of this study's evidence of associations between the type of NBS a park has adopted and its landscape and sociodemographic contexts. Hues of red represent higher values and positive associations, and hues of blue represent lower values and negative associations. Color brightness illustrates the level of confidence for the results, with darker colors representing statistically significant results, and lighter colors representing descriptive results with repeated max and min values but not statistically significant.

ECO was the most used NBS practice across the parks included, especially for addressing coastal/riverine flooding. Further, parks with ECO adoption tended to have high flood risks within the park boundaries and in their surroundings, as well as more greenspace in their surroundings. These results indicate that parks with ECO are likely to be located on or near waterways and shorelines within a less built area. Choosing an ECO type of NBS for these parks may be a strategy to take advantage of better baseline environmental conditions and to further expand the existing greenspace through habitat restoration or construction. There has been an ongoing effort for daylighting buried urban channels and restoring the floodplain of channelized streams in the past decades to improve water quality and habitat, with a growing primary focus on flood control [74]. In coastal areas, the idea of using NBS such as living shorelines to enhance coastal resilience is also drawing more attention, including the adoption of living shorelines in urban parks [75]. Based on our findings, we argue that an equally critical direction is to develop novel, hybrid NBS that can effectively address increasing extreme precipitation and coastal weather events by leveraging both native ecosystems and new engineering techniques through interdisciplinary collaborations among marine ecologists, coastal engineers, and landscape architects [76]. In addition, our study provides some evidence that parks with ECO might tend to be located in neighborhoods with higher percentages of underage populations and lower percentages of Asian populations. Including educational programs that prioritize youth for parks with ECO may contribute to effective public outreach strategies and broader awareness and acceptance of NBS for flooding.

SGSI was most often used in parks that focused on stormwater-related flooding. Parks with SGSI adoption on average had the lowest flood risks within the park boundaries and in their surroundings. In addition, they also had the highest percentage of built areas in their surroundings as well as significantly lower percentages of greenspace compared to parks with ECO and POND. These results match the primary designed function of SGSI—to collect and treat stormwater runoff with soils and plants at or near where it is generated. This function is particularly suitable in urban upland locations of high imperviousness [77]. Reflecting on the dominant use of SGSI in parks to manage stormwater-related flooding, we caution on a planning and design approach to NBS that narrowly picks feasible options from a portfolio of techniques [22,44]. Rather, diverse NBS including detention basin and floodable landscapes (TEM), retention ponds (POND), and restored or constructed wetlands (ECO) should be considered and explored to maximize environmental and social co-benefits.

ENG was the least used type of NBS in this study. This result contrasted with Tong et al. (2022), who found that permeable pavement in pathways and open spaces—an ENG practice based on our NBS typology—was the most common stormwater management measure in the Sponge City Parks in Shanghai and were used in all 21 parks they examined [40]. Despite the lower use of ENG overall, ENG was more often used than all the other types of NBS in parks that addressed both stormwater and coastal/riverine flooding. This might be due to a tendency to adopt highly engineered NBS rather than natural systems when risks of compound floods are present. In addition, parks with ENG are located in neighborhoods with notably, though not statistically significant, higher percentages of Asian populations, lower percentages of Black and underage populations, and fewer cars owned per household. To the extent that ENG practices typically provide few social co-benefits, future research is needed to better understand whether the ENG type of NBS is more likely to be adopted in parks in underserved communities and the related implications for equity.

TEM was the top type used in parks with multiple NBS adoption, often combined with POND and ECO. For example, the combination of detention basin and retention ponds was present in Utah Park in Aurora, CO, and the combination of riverbank restoration and temporary flooding accommodation was present in Waterfront Park in Louisville, KY. With increasing extreme precipitation events under climate change, design strategies that create flexible uses and can accommodate both wet and dry weather needs are on the rise [78,79]. Urban parks are a suitable location to create relatively large detention and

floodable landscapes since there is much open space for outdoor activities that take place only in dry weather. Such space can be leveraged to temporarily store runoff and flood water during and shortly after a storm hits, though it is important to tailor the design of TEM type of NBS with community members' flooding experiences since they could be perceived as unsafe [80].

Parks with **POND** adoption on average had the highest percentage of greenspace in their surroundings. Pairwise comparisons showed that they had significantly higher percentages of greenspace than parks with SGSI and ENG, and significantly lower surrounding flood risks than ECO. In addition, they were located in neighborhoods with notably, though not statistically significant, lower poverty rates and higher percentages of senior populations. These results suggest that POND may likely be adopted by parks in communities that are wealthier and have a better coverage of greenspace, although these communities may not have very high flood risks. Given that retention ponds may contribute to the value increase in nearby homes [81], extra attention is needed to best enhance equity and avoid green gentrification when siting and designing the POND type of NBS.

In addition, this study indicates notable differences between visitation-based and proximity-based sociodemographic contexts. Specifically, we found individuals and families that are wealthier and White more often visited parks with NBS. Even when NBS practices are adopted in parks located in neighborhoods that are less wealthy and have more minorities, the residents may not receive as many NBS social benefits due to less use of the park. This finding suggests potential inequity in the delivery of social benefits by park NBS that is influenced by park visitation preference. It is important, therefore, to not only site NBS in underserved communities but also utilize inclusive processes to engage members of underserved communities in the planning, design, and implementation of NBS [82]. Further, disadvantaged communities need NBS types with more co-benefits beyond flood control.

4.3. Limitations and Future Research

This study has several limitations that demand caution when interpreting or generalizing the results. First, inherent limitations in the study sample may bias the results of this study. We used the 2022 City Park Fact Survey conducted by the Trust for Public Land to collect parks to be investigated and to obtain information about NBS practices adopted in these parks. Since the City Park Fact Survey targets the 100 most populous U.S. cities, and the 2022 Survey only asked park and recreation agencies to provide examples of climate resilience-building practices, the survey data cannot represent all public parks in the U.S. that have adopted NBS to address urban flooding. For example, compared to the summary of the Fifth National Climate Assessment [68], our study sample included few examples from the Northeast, a region that has experienced extreme precipitation and problematic flooding in recent years and undertaken notable efforts to build resilience using NBS. In addition, the survey combined coastal and riverine flooding—which are often viewed as two distinctive sources for urban flooding—into a single climate impact. While the use of the 2022 City Park Fact Survey served this study's exploratory nature well, the study findings should be interpreted with caution and without generalizations. Second, we did not account for the time of various secondary datasets and assumed a relatively stable status of the parks' landscape and sociodemographic contexts in the data analysis. For example, when determining the value of average weekly visitation-based sociodemographic contextual variables, mobility data from year 2022 and the 2016–2020 American Community Survey 5-Year Estimates data were combined. Third, the Adavn mobility data, from which we obtained the park visitation records, were extracted from cellphone-based geolocation data. This is subject to varied sampling rates among different geographic areas and population groups, with a potentially poorer representation of people with low socioeconomic status

of minority groups; therefore, the mobility data may result in biased measures for the visitation-based CBGs in our study.

Future research can focus on specific cities faced with urban flooding challenges as case studies and examine NBS adoption in all parks across the city. Emphases should be put on, first, the relationships between NBS adoption, NBS type, and community sociodemographic status, based on the limited but notable evidence of inequity in social benefits delivery from this study; and second, how varied sources of urban flooding (e.g., stormwater, coastal, riverine, and flash) may affect NBS adoption in terms of siting location and practice type. Further, research on NBS and park contexts can be complemented by investigations of the NBS planning and design rationale through, for example, policy analysis and interviews with managers and designers. More research is also needed to evaluate the flooding mitigation efficacy as well as ecological and social co-benefits of park NBS given their widespread adoption and potentially significant role in enhancing urban resilience and affecting nature experiences in cities.

5. Conclusions

Nature-based solutions (NBS) are gaining increasing attention in discourse and actions for flood resilience. This study explored the adoption of NBS for urban flood management in public parks, a critical community asset to protect and expand nature in cities. We found that diverse NBS practices have been adopted in public parks in many U.S. big cities to address stormwater-related and coastal/riverine flooding under climate resilience and adaptation efforts. We developed a high-level typology of park NBS practices and provided new insights into the relationships between NBS type and a park's landscape and sociodemographic contexts. Our findings suggest that the choice of what NBS type to implement in a park is associated with its surrounding land cover, surrounding and interior flood risks, and neighborhood sociodemographic status. We also found that, overall, park visitors were more privileged compared to residents living near a park. These observed trends have implications for the success of park NBS in delivering co-benefits in an equitable manner and warrant further research to confirm their generalizability and to explore effective planning and design strategies.

This study addresses the limited research on park NBS adoption and broadens the focus of NBS practices from flooding management techniques to landscape design and planning that approach urban flood resilience as a societal challenge. We argue that landscape and sociodemographic contextual factors deserve explicit consideration in the adoption of park NBS. To the extent that parks make up key multifunctional urban greenspace, the siting and design of park NBS must build on a comprehensive understanding of the local environment and community. Further, park managers and designers should consider a diverse portfolio of NBS and, when necessary, develop novel hybrid practices to effectively enhance urban flood resilience and deliver co-benefits.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13091531/s1.

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Designing Stress-Relieving Small Inner-City Park Environments for Teenagers

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Abstract: All over the world, teenagers suffer from stress-related mental illness, and research shows that being in natural environments can bring about recovery. However, centrally located areas in cities where teenagers like to hang out are being densified at the expense of green spaces. The health-promoting function of small, centrally located parks is thus becoming increasingly important. This study examines Iranian teenagers' assessment of the restorative potential of small, centrally located parks. Such parks include attributes typical of city centers, such as trees, lighting, park benches and flowers. A discrete sampling method was used to collect responses from a sample of 265 Iranian teenagers. They were asked to randomly rate the perceived recovery potential of digitally designed models of green spaces. The results show that the teenagers evaluated the presence of water in waterbeds to have a strong positive effect on recovery possibilities. The entire green area should also be screened off from the rest of the city and convey a soft impression. It should have lighting from tall lampposts, contain plant beds and, not least, have distinctive cultural attributes such as crescent arches and fountains. In the discussion of the article, we address the practical and theoretical implications of the findings.

Keywords: restorative environment; stress reduction; attention restoration; evidence-based design; perceived sensory dimensions

1. Introduction

The teenage years are a sensitive phase in human development, as they involve a transition from childhood to social, psychological and physical maturity. During adolescence, humans must adapt to peers and learn to understand and function in adult life. At the same time, great demands are placed on them from school, parents, peers, society, influencers and social media about how a teenager should be and look in order to be accepted. Research shows that teenagers often suffer from stress, loneliness, low attention span and depression and feel maladjusted [1,2]. In addition, many are far too sedentary, which might lead to obesity and an increased risk of type 2 diabetes and cardiovascular disease [3,4]. A growing problem which may explain ill health is that teenagers spend more and more time indoors alone, where a lot of time is spent on computers and mobile phones. They need to socialize more with other age groups, as well as with other teenagers [1–5]. Early socially, physically and psychologically stimulating environments, not least in adolescence, seem crucial in avoiding mental and physical ill health in adolescence and later in life [3,5]. Extensive research shows that staying in urban green areas is positive for people's health, showing statistically significant relationships with increased physical activity, increased social togetherness, better mental health, lower stress levels and increased ability to focus

attention [6–10]. In addition, several research studies show that urban parks can be health-promoting assets in terms of offering teenagers opportunities for physical activities [11–14], social stimulation [14–16] and mental recovery [17–21].

1.1. Teenagers' Need for Parks

In order to plan and design health-promoting parks for teenagers, it is important to understand their needs for parks: how they are used, as well as teenagers' preferences for the appearance and content of parks. Three researchers who carried out important early studies in the field are Mats Lieberg, Herb Childress and Patsy Owens. They discovered that teenagers like to seek out centrally located public environments where people like to hang out and where various activities are often taking place. This naturally leads to social relations in public open spaces. The researchers found that the public space acts as a stage for teenagers where they can display their external attributes, such as clothes, music taste and appearance, expressing themselves verbally but also showing off their skills in, for example, skateboarding [22–24]. It is, however, also about teenagers withdrawing from the outside world and the adult world to be with peers and other teenagers. In these latter cases, there is a clear need to avoid other age groups and to be able to meet other teenagers and teenage groups. However, in addition to the need for community, teenagers also need more private and quiet refuges as a counterpoint to the stress and bustle of everyday life [22,23]. Thus, a couple of clear landscape features that support these needs can be identified: places where teenagers can retreat to socialize, places for interaction and confrontation with all age groups, not least with the adult world [22], and retreat sites with natural features, preferably sites that offer clear prospect-refuge sites [25]. But teenagers are often met with annoyance, as they can be loud and lively at times. Thus, the presence of teenagers in a park can lead to other age groups hesitating to visit or even avoiding the park [24]. A solution that has sometimes been implemented is to create specific parks for teenagers. However, designing special places for teenagers does not work at all. Such attempts have been proven to isolate rather than integrate teenagers into the broader community. In addition, they may avoid places designed specifically for teenagers. An alternative approach to design and policy must be to integrate teenagers into existing public spaces by adding certain design attributes, rather than developing places specifically for teens [23,26–29].

Recent years of research have largely confirmed the research results of the three pioneers. Teenagers often choose to visit centrally located public open spaces [15,30,31]. They want to seek out public environments where people like to hang out and where various activities are often taking place [20,21,32] to be able to do sports and play [14,31,33–35], but also to be able to withdraw alone or with friends to de-stress [20,30]. The result of several research studies is that what primarily determines whether teenagers choose to visit parks depends on the distance to and/or accessibility of the parks [14,21,31]. Others claim that it mainly depends on the size of the parks [17,36] or the maintenance of the parks, such as whether they are clean and whether benches and playground equipment are intact and functional [33,37]. However, several other studies claim that it mainly depends on whether the park is judged to be safe and secure to stay in [12,15,20,38].

Rigolon and Németh [39] have summarized requirements for parks for teenagers by introducing a quality index of parks for youth (QUINPY). It contains the parameters of structured play diversity, natural features, park maintenance, park safety and park size. The size is—as e.g., Feda et al. [17] and Costa et al. [36] state, an important characteristic of parks. If the park is large enough, it provides space to do more physical activities [31], to be able to get away from noise [34,38], to be able to withdraw from the hustle and bustle of the city [17] or to be able to feel that you are left alone and at peace—with friends or by yourself [20,30]. If the park is large enough, it can also become multifunctional [36].

Research covering all age groups also shows that larger green areas provide space for more physical activities, but also space to get further away from the city's noise, rushing people and traffic, and thus increase the opportunities to reduce high stress levels and restore capacity regarding directed attention fatigue [40–42]. However, in the endeavor to

achieve sustainable urban planning, the smart, compact and green city has been highlighted as an ideal, characterized by high density, mixed land use and attractive green infrastructure. In the pursuit of an increasingly dense city, many green areas are thus disappearing, while researchers warn of the consequences this will have [43–45]. The restorative value of small urban green areas is thus of great interest within the framework of the smart compact city, where the content, functions and design of green areas are valued for their contribution to urban sustainability [9,46,47].

1.2. Health-Promoting Small and Centrally Located Parks

However, relatively few studies have investigated the health-promoting value of small centrally located parks. They often contain cultural attributes such as sculptures, fountains and flower plantings [48–51]. From a theoretical perspective, small parks with cultural content can be health-promoting. Stephen Kaplan [52] argues that well-designed small parks with cultural content, such as Japanese rock gardens, should be able to provide recovery from attention fatigue. Likewise, Roger Ulrich claims that small health gardens at hospitals can provide recovery from high stress levels [53]. Small urban parks with cultural content should therefore be able to promote health in terms of stress recovery and recovery from attention fatigue. Some studies also show that small urban parks lead to mental recovery [48,54,55] and attract visits, even if people have to walk longer distances [50]. The mental recovery provided by small parks cannot be related to physical activity, but to how the design and content of the parks work restoratively when the visitor is affected by high stress levels and/or attention fatigue [54]. Although the slightly larger pocket parks may provide better opportunities for recovery, the design of the parks seems to be most important, where above all, vegetation is found to be decisive [48,55]. Research shows that the cultural characteristics of urban parks give them identity and contribute to a sense of place, placing attachments to personal as well as community mental health [56–59]. However, studies of young people's demand for qualities in urban environments show that cultural attributes are often missing in larger cities [60,61].

Many researchers claim that more research is needed to find out how parks should be designed to meet the user needs of teenagers, who are considered to be an understudied group [62–66]. Wales et al. [67] argue that there is a great need for research that can identify specific design attributes of outdoor environments that support young people's health and well-being. We find that this particularly applies to centrally located small parks. Consequently, the aim of this study was to investigate design features regarding their attractiveness and ability to provide teenagers with mental recovery. The goal is to present a number of attributes that can be used in the design of small centrally located parks, which can increase the attractiveness of the parks and promote mental recovery.

2. Methods

The main purpose of this study was to investigate and evaluate the effect of design attributes in small centrally located parks regarding mental recovery in teenagers. To achieve this goal, this study used the discrete choice method, which analyzes individuals' preferences based on their choices. Individuals were presented with a set of hypothetical options and asked to select their preferred option based on their priorities and preferences. Each option consisted of a combination of different levels of functionality. This method enables researchers to explore individuals' values and priorities regarding the desired characteristics of a product or service [68]. Unlike most studies that rely on written descriptions of park features [69], this study incorporated visually visible features by providing participants with designed, digital color photographs. Studies show that exposure to realistic natural environments gives participants opportunities to experience their health-promoting properties. In a study where participants were exposed to a digital virtual environment, they experienced significant improvements in vitality, mood and perceived restoration outcomes [70]. This discrete choice method has been widely used in health economics research in high-income countries [71]. In addition, it has been used in various other

research domains, including tourism, transportation, economics, health, architecture and sports activities [33,72–74]. All images in figures and tables in the article were made by the authors.

2.1. Participants

The respondents voluntarily participated in this research. Only individuals between the ages of 13 and 19 were eligible to participate in the survey, as this aligned with the research subject [75]. Questionnaires were distributed among educational groups, and participants were asked to complete a consent form to participate in the study. For those participants who were under 18 years of age, i.e., underaged, consent was also required from the guardian. No sensitive information was collected, all data were anonymized and all aggregations of responses were at the group level. All study participants—together with their parents/guardians if underaged—gave their written informed consent to participate in the study, which was in accordance with our professional regulations, the Code of Ethics of the World Medical Association and the Declaration of Helsinki [76], obtaining ethical approval for this study. When they expressed their consent, the questionnaire was activated.

2.2. Primary Outcome

Perceived restorative potential (PRP) is a global, valid and reliable measure of how participants assess an area's capacity to help them recover from being overwhelmed, stressed and exhausted. It has come to be used more and more frequently and has been used in several studies similar to this one [77,78]. Perceived restorative potential is measured by instructing subjects to do the following: recall a time when you felt overwhelmed, stressed, tired and anxious. Reflect on how you felt in that moment and put yourself in that mind set. Continue to reflect on this mind set as you view the pictures and imagine yourself in each environment. For each of the images presented, rate the degree to which you think being in that environment would be good for you to take a break and make you feel less stressed and anxious, using a scale from 0 (not a good place for a break at all) to 100 (very much a good place for a break).

In this study, the instructions were modified dependent on the participants being students and read as follows: "Imagine it is the middle of the day, the weather is relatively pleasant. Your class has just finished and you are leaving the school premises. You are walking home alone and feel mentally tired due to concentrated effort during the lessons. Therefore, you need a short break for maximum recovery before returning home and continuing academic pursuits." Based on this question, the participants chose the park that they believed could best provide them with rest and recovery.

2.3. Identification of Design Attributes and Levels

In the development of evidence-based health design, knowledge is needed about how both overall qualities and the design of individual attributes and details can work in a health-promoting way [9,79]. A large number of attributes with different designs have been highlighted in various research studies, and there has been a need to bring some order to this—some kind of hierarchy of superior and specific characteristics. Not least, it is important to be able to use the results in practical design and planning [79]. An increasingly used way of describing the overall spatial characteristics is the eight Perceived Sensory Dimensions (PSDs) [80]. These have been shown to be valid and reliable when it comes to describing the overall characteristics of green areas [60,81,82]. Knowledge of the unique characteristics of these eight PSDs and their attributes needs to increase in order to better plan and design attractive and health-promoting parks [83–85].

Dense inner-city environments often have small parks, and if well-designed, people may experience one or more PSDs in these environments. The PSD that visitors most often experience in inner-city environments is PSD Cultural, which often co-occurs with and is enhanced and supported by PSD Social, PSD Diverse and PSD Sheltered [86]. PSD

Cultural consists of attributes such as fountains, sculptures, planting beds, trees, flowers, exotic plants and water elements such as canals and ponds [80,87,88]. PSD Social is about social meeting places, with features such as paths, lighting, benches and tables [88]. PSD Diverse is about a variation in shape and color in the park, for example, regarding trees and flowers, while PSD Sheltered contains functions that allow the visitor to be protected and have control over the environment, which can be facilitated by bushes, small hills and fences [80,87,88]. Several other studies also mentioned these attributes being important in green areas with a cultural character, but also added arches and garden streams [89–91]. Several studies of small, centrally located parks suggest a number of important levels or variations of these attributes, which we chose to include in this study (below and Table 1).

Table 1. Attributes and their related levels.

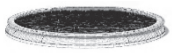
Attributes	Levels	Description		
Water features	**Pond** **Garden stream** **Fountain**			
Seating	**Wooden** **Concrete** **Metal**			
Arch	**Square arch** **Crescent arch** **Not present**			
Pavement	**Paving stone** **Natural flagstone** **Paving stone–grass**			
Lighting pole	**High-base** **Medium** **Short-base**			
Sculpture	**Present** **Not present**			

Table 1. *Cont.*

Attributes	Levels	Description		
Fence	**Wooden** **Concrete** **Metal**			
Raised planting bed	**Present** **Not present**			

Based on our literature review, the following attributes and levels were finally selected. We chose three levels of water features, namely ponds, fountains and garden stream [69,92–94]. Moreover, we chose three types of seating: wooden, concrete and metal park benches [95–98]. In addition, we chose two levels of arches in this study: square and crescent [90,91,99]. Based on our reviewed studies on pavement, we chose paving stone, natural asymmetric flagstone and paving stone–grass surfaces as suitable levels for pathway paving [33,48,92,100,101]. We chose to investigate the design of lighting poles at three different levels—long-base, medium-base and short-base [89,100,102,103]. Based on the reviewed literature, we chose a colorful symbol of traditional Iranian windows and decorations, which was presented in the form of a sculpture in the park, which can attract young visitors [66,96,104,105]. The levels of the sculpture attribute were present or not present. We chose three types of material regarding fences in our study: wooden, concrete and metal [48,100,103,106]. The last attribute we chose to examine was raised planting beds, where we examined environments with or without raised planting beds [66,69,103].

Table 1 shows all selected attributes and their respective levels in this study. These were inserted into images with different scenarios where grass, trees and flowers were included as fixed elements.

2.4. Scenarios and Choice Sets

In the experimental design process, a combination of six three-level factors and two two-level factors was used to generate a diverse range of colored digital scenarios that participants might encounter. While the full factorial design would have resulted in 2916 (2^2*3^6) possibilities, this approach was deemed impractical due to the sheer number of choices and the potential complexity of the questionnaire. Instead, a fractional factorial design utilized to identify a subset of optimal choices. Not only did this method reduce the number of tests required, it also facilitated the optimization of both the selection process and questionnaire content. Using SAS version 9.2, the attribute and level evaluation yielded 72 options (or 36 selection sets) for park design [107]. Subsequently, digital simulations were conducted in SketchUp software version 2020, producing 72 distinct digital scenarios that were organized into six blocks, each containing six selection sets. Next, a digital virtual park was created using the selected attributes and levels listed in Table 1, with the aid of the fractional factorial design. The initial park design encompassed a compact local park spanning around 6500 square meters, modeled after an Iranian garden and situated amidst residential areas, roads and mountains. The design incorporated various desired features conceived by the researchers, along with some design attributes that were adapted and modified from pre-existing SketchUp digital models obtained from the 3D Warehouse repository. In the final design, the garden stream was changed from a curved basin to a rectangular pool, and the boundaries of the raised planting bed were made significantly lower than in the original design (Table 1). A random classification procedure was applied to the collection of alternatives, ensuring that each block contained six sets of selections.

Each block presented 12 digital model views in the same size and position. The design of the assessed digital view was deliberately curated to guarantee that all relevant attributes and levels corresponding to the block classification were clearly visible to the respondents (Table 2 and Figure 1). Ultimately, the digital designs were exported as high-quality mpg files using V-Ray software version Next v5.10.02, ready to present in the survey.

Table 2. An example of block classification extracted with SAS version 9.2.

Alt	Water Features	Bench	Lighting Pole	Pavement	Raised Planting Bed	Fence	Sculpture	Arch
alt 1	fountain	wooden	high-base	paving stone	present	metal	present	crescent arch
alt 2	garden stream	metal	medium-base	concrete–grass	present	wooden	not present	not present



Figure 1. Shows an example of a digital model of the visual questionnaire design based on block classification in Table 2.

Table 2 shows an example of block classification extracted with SAS version 9.2.

2.5. Online Survey Design

Thirty-six choice sets were prepared to evaluate the environments, using SAS software as described previously. However, answering 36 choice sets per participant can lead to fatigue. To address this, the choice sets were divided into six blocks, each consisting of six choice sets of digital color models. Participants were randomly assigned to answer questions from a single block, consisting of six choice sets from a digital view. The survey had two sections. Demographic information was collected in the first part, while the second part contained discrete choice questions from digital models that were divided into six blocks. Participants were presented with a scenario, "Imagine it is in the middle of the day…", before answering the questions in the second section. They could choose one of the blocks at random. After viewing the design options displayed as digital color landscape models (Figure 2), they were able to select their preferred park according to perceived restorative potential.

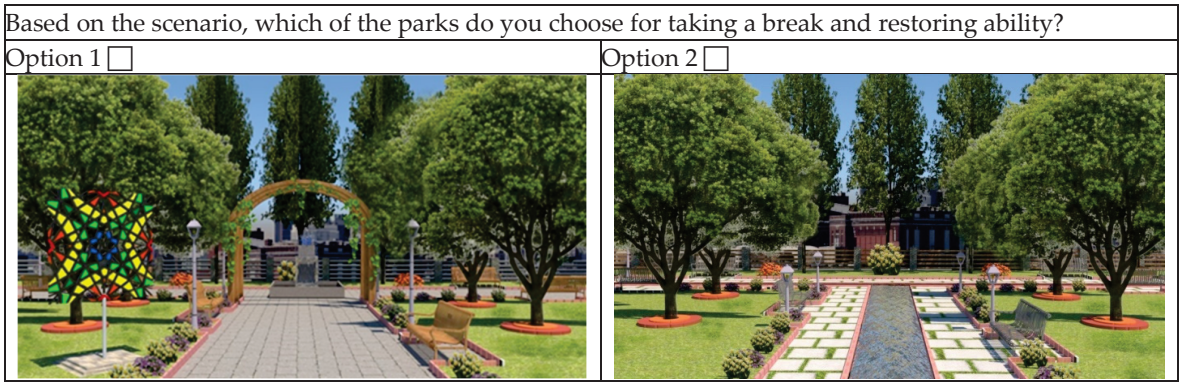


Figure 2. An example of the discrete choice questions with two digital models.

2.6. Data Collection

Considering that the COVID-19 pandemic was ongoing in Iran in July 2021, the data collection was conducted online. First, the digital model options and survey questions were reviewed and approved by experts. To gain access to survey participants, administrators of private educational institutions and schools were asked to add the article's first author to their lists of social information groups. An invitation link to the survey was then disseminated via social media (WhatsApp, Telegram) and email to recruit participants. The data collection was self-administered, where instructions were given and all information was then filled in by the participants themselves. That is, before the survey was sent and started, the first author of the study wanted to make sure that the participants understood the purpose of the study by giving a clear explanation. Instructions on how to proceed with the survey were also provided. Participants were first asked to complete a demographic questionnaire that included questions about their age, gender and level of education and field of study. After completing the demographic questionnaire, participants were shown digital models of different blocks and asked to choose which park they would prefer to visit to alleviate feelings of exhaustion, given the scenario presented to them. To ensure accurate results, participants were made aware of the different attributes present in the digital models. They were asked to carefully evaluate each model when making their decisions, focusing on the potential impact of the selected parks on their recovery. It was also emphasized that the model should be close to home or school. The third part of the survey contained a set of questions for the respondents. These questions were related to park visits, such as the proximity of their residence to the local park, the number of times they usually visited the park, their usual length of stay and their mode of transportation to the park. Two additional questions were asked: whether the urban small park was effective in motivating walking, ball sports and use of sports equipment, and whether the urban small park helped with weight loss and the risk of being obese.

2.7. Modelling Choice Data

The mixed logit model is one of the highly flexible discrete choice models that can provide many interpretations based on different behavioral characteristics by finding heterogeneity in people's behavior and the source of heterogeneity [108]. It is an advanced and improved model of the multiple logit model that solves the limitations in the estimation of utility types by using a variety of random experiments, unlimited substitution patterns and correlation in unobserved factors in time [109].

Notably, unlike standard logit and probit models, this model is not confined to a specific distribution, and it can capture more complex choice patterns, individual heterogeneity in behavior and even the sources of this heterogeneity. The probability of choice by different individuals, individual-specific tastes and sensitivities can all be computed. Moreover, individuals may face uncertainty in their choices, which the mixed logit model takes into account when analyzing the data. In the multinomial logit approach, the odds ratio of choosing one alternative over another is independent of the other alternatives. This assumption is often unrealistic, and the mixed logit model overcomes this limitation, enabling the modeling of more complex dependencies. Therefore, when the assumption is that individuals in a study have varying preferences and the relationships among variables are more complex, the use of the mixed logit model is recommended. This method allows for the modeling of heterogeneity and more intricate relationships using probability distributions for the parameters, leading to results and predictions that are more accurate. Additionally, when the research objective is to gain a deeper understanding of individual behavior and the factors influencing it, and the analysis of how explanatory variables affect individual preferences is crucial, this method is often used.

In the investigation of the mixed logit model, based on research by McFadden and Train [108], it was determined that if appropriate distributions for the properties of the coefficients in a random utility function were considered, the behavior of different random utility models would be expressed in approximately the same way. In addition to the fact

that the normal distribution and the normal logarithm distribution are widely used in mixed logit modeling, providing suitable results, the use of triangular distribution [110] and restricted distributions such as the SB Johnson distribution [111] also provide suitable and significant results. Therefore, it is very important to choose the right type of distribution for the coefficients of the random utility function to obtain accurate results. The main assumption of discrete choice models is that when the decision-maker is faced with a choice set, they choose the option that has the most utility and attractiveness to them. This criterion of utility, which leads to a choice based on the personal preferences of the decision maker, is a function of the options' features and the decision-maker's characteristics. It should also be kept in mind that the decision-maker is faced with a set of independent options that they can only choose one of, and they are not able to choose an amount or part of each. For this reason, this method is called discrete choice [112].

The utility function of option j for person q is expressed as U_{jq}. This utility has two parts: a definite/observable part (V_{jq}) and random/unobservable part (ε_{jq}).

$$U_{jq} = V_{jq} + \varepsilon jq$$

In the mixed logit model, the random part of the utility function (ε_{jq}) consists of two parts: the arbitrary distribution and the distribution of the limit value with the independent and identical distribution. As a result, fewer assumptions are made for the data. In fact, the mixed logit probability is the integral of a multinomial logit selection probability function over a density function (weight) based on different values of β (density of parameters). The probability of person q choosing option j (P_{jq}) is given by the following equation:

$$P_{jq} = \int Ljq\ (\beta)\ f\ (\beta) d\beta$$

Here, P_{jq} is the probability of choosing option j by person q. Also, $Ljq(\beta)$ is the probability of choosing option j by person q, which is a function of parameter β and is expressed as follows:

$$L_{jq}\ (\beta) = \frac{e^{v_{jq}(\beta)}}{\sum e^{v_{mq}(\beta)}}\ m \neq j \subset C_q$$

where $f(\beta)$ is the density function of parameter (β) and $v_{jq}(\beta)$ is the observed component of the utility function of option j by person q, which depends on parameter (β). Finally, the probability function of choosing the combined logit model is defined as the following relationship:

$$P_{jq} = \int \left(\frac{e^{v_{jq}(\beta)}}{\sum e^{v_{mq}(\beta)}} \right) f(\beta) d\beta$$

Therefore, the probability function of choosing the mixed logit model is a weighted average of the probability function of choosing the polynomial logit model over different values (β). To describe the density of β, the mean b and the covariance W can be used normally [109].

The random coefficients model is one of the simplest and most widely used models that can create different interpretations based on the preferences of decision-makers by considering the utility-maximization behavior in different ways in the mixed logit probability analysis. In this model, the defined utility of option i to choose among options I for person q is given by the following equation:

$$U_{iq} = \acute{\beta}_q X_{iq} + \varepsilon_{iq}$$

Here, X_{iq} is the observed characteristics of the decision-maker and the option. $\acute{\beta}_q$ is the vector of coefficients of the observed characteristics for person q, which shows people's preferences. ε_{iq} is also the random part of the utility function, with a limit value distribution with an independent and uniform distribution. The mixed logit model has two sets of

parameters, unlike the standard logit model. In the first set, we have β parameters, which enter the logit formula; the density function $f\ (\beta)$ represents them and is different for decision-makers. The second set is the parameters that define this density, specified by θ. If β is normally distributed with mean b and covariance W, then b and W are parameters describing the density $f(\beta)$. A more appropriate way to represent the parameters of the second category is $f(\beta \mid \theta)$. As a result, the random coefficients model, as an integral of the logit model, is defined on the parameter density function as follows:

$$P_{qi} = \int \frac{e\left(\acute{\beta}_q X_{qi}\right)}{\sum_{j=1}^{J} e\left(\acute{\beta}_q X_{qi}\right)} f(\beta|\theta) d\beta$$

In this definition, the decision maker knows the value of βq and ε_{iq} for all j; if and only if $U_{qi} > U_{qj}\ A_j \neq i$, it chooses alternative i. The researcher observes X_{iq} but not βq or ε_{iq}, so it cannot condition β. If the researcher observes βq, the probability of the selection will be a standard logit [109].

3. Results

A total of 265 adolescents, all of whom were ordinary Iranian citizens, participated in answering the questionnaire, of which 66% (175 individuals) were female and 34% (90 individuals) were male (Table 3). The participants were categorized into two age groups: 13 to 15 years (81%), with 215 people, and 16 to 19 years (19%), with 50 people.

Table 3. Baseline characteristics of study participants regarding demographics and visits to urban parks.

Characteristics		Number (N = 265)
Gender		
Male		90
Female		175
Age (years)		
13–15		215
16–19		50
Education		
Primary		131
High school		112
Diploma		22
Distance to the nearest city park	300 m	73
	300 m–1 km	110
	1–5 km	53
	>5 km	29
How to get to the park	Walking	151
	Bicycle	31
	Private vehicles	79
	Public transportation	4
Number of visits to the park during the warm months	Never	60
	A few times during the season	99
	At least once a month	55
	At least once a week	33
	A few times a week	18
Duration of rest in the park	30 min	81
	30 min to 1 h	93
	1 to 2 h	60
	2 to 3 h	19
	More than 3 h	12
Effect of the park in creating motivation for walking, ball sports and use of sports equipment	Poor (0)	16
	(1)	12
	(2)	11
	Moderate (3)	35
	(4)	33
	(5)	46
	Excellent (6)	112

Table 3. *Cont.*

Characteristics		Number (N = 265)
Effect of the park in reducing obesity and weight loss	Poor (0)	14
	(1)	6
	(2)	15
	Moderate (3)	68
	(4)	37
	(5)	44
	Excellent (6)	81
How important is it for you to rest, clear your mind and reduce your stress when visiting a small city park?	Poor (0)	9
	(1)	9
	(2)	7
	Moderate (3)	61
	(4)	24
	(5)	48
	Excellent (6)	107
Based on your experience, how much does spending time in a small city park help you to have peace of mind, clear your mind and reduce stress?	Poor (0)	10
	(1)	11
	(2)	13
	Moderate (3)	52
	(4)	39
	(5)	49
	Excellent (6)	91

The schools included in the study had significantly more younger students than older students, so in that case, our material was fully representative. In contrast, the distribution of men and women was equal in the schools included in the study. All students were invited to participate, but according to ethical approval, participation was voluntary and unfortunately, fewer men participated. To compensate for the bias in the statistical material, weighting was used [113].

The results of the participants' choices were analyzed using the Random Parameter Logit (RPL) model and the PandaBiogene software. This analysis aimed to investigate the level of heterogeneity in the answers, examine the main effects of desired digital view visual features and conduct further analysis. The payment results of the model are presented in Table 4.

Table 4. Evaluation of parameters in 36 digital model based on the mixed logit model.

Attributes and Levels						Interaction Effects		
Random Parameters	**Base Level**	**Value**	**Std err**	**t-Test**	***p*-Value**	**Age**	**Gender**	**Education**
ASC_1	$\beta 0$	0.0816	0.022	3.71	0.000208			
Arch								
Square arch (mean)	$\beta 1$	−0.269	0.0409	−6.57	5.06×10^{-11}	-	-	-
Square arch (St.dev)		0.229	0.0486	4.71	2.45×10^{-6}			
Not present (mean)	$\beta 2$	−0.269	0.0537	−5.02	5.16×10^{-7}	-	-	-
Not present (st.dev)		0.603	0.058	10.4	0			
Lighting pole								
High base (mean)	$\beta 5$	0.314	0.0419	7.51	5.88×10^{-14}	-	-	-
High base (st.dev)		−0.267	0.0497	−5.38	7.29×10^{-8}			
Pavement								
Paving stone–grass (mean)	$\beta 8$	0.169	0.0398	4.24	2.25×10^{-5}	0.00528	-	-
Paving stone–grass (st.dev)		−0.206	0.0564	−3.65	0.000265			
Sculpture								
Not present (mean)	$\beta 11$	0.222	0.0437	5.09	3.62×10^{-7}	-	0.0558	-
Not present (st.dev)		0.492	0.0519	9.49	0			
Water features								
Garden stream (mean)	$\beta 12$	0.490	0.0543	9.03	0	0.00124	0.015	-
Garden stream (st.dev)		−0.599	0.0716	−8.37	0			
Pond (mean)	$\beta 13$	−0.13	0.0391	−3.31	0.000936	0.0356	-	-
Pond (st.dev)		0.124	0.051	2.43	0.0151			

Table 4. *Cont.*

Attributes and Levels						Interaction Effects		
Random Parameters	**Base Level**	**Value**	**Std err**	**t-Test**	***p*-Value**	**Age**	**Gender**	**Education**
Non-Random Parameters								
Fence								
Wooden (mean)	$\beta 3$	−0.152	0.0385	−3.94	8.14×10^{-5}	0.0646	-	-
Wooden (st.dev)		0.0372	0.0498	0.747	0.455			
Metal (mean)	$\beta 4$	−0.0774	0.0388	−1.99	0.0463	-	-	-
Metal (st.dev)		−0.037	0.0471	−0.785	0.433			
Pavement								
Natural flagstone (mean)	$\beta 7$	0.109	0.0383	2.84	0.00451	-	-	-
Natural flagstone (st.dev)		−0.0815	0.0494	−1.65	0.0993			
Bench								
Metal (mean)	$\beta 10$	0.0785	0.0399	1.97	0.0493	-	-	-
Metal (st.dev)		−0.0614	0.0507	−1.21	0.226			
Non-Effect Parameters								
Lighting								
Short base (mean)	$\beta 6$	−0.0554	0.0393	−1.41	0.158	0.0208	-	-
Short base (st.dev)		0.0774	0.0526	1.47	0.141			
Bench								
Concrete (mean)	$\beta 9$	0.0372	0.0386	0.964	0.335	0.0045	-	-
Concrete (st.dev)		−0.0198	0.0505	−0.392	0.695			
Raised planting bed								
Not present (mean)	$\beta 14$	−0.014	0.0321	−0.437	0.662	-	-	-
Not present (st.dev)		0.146	0.0389	3.74	0.000181			
Goodness of Fit Measure								
$\rho_0{}^2 = 0.0844$		LL(0) = −6741.938		LL(ß) = −6173.069		LL(R) = 1137.738		
$\rho_0{}^2 = 1 - \frac{LL(ß)}{LL(0)}$		$\rho_0{}^2 > 0$		$X_{29}{}^2$ (0.95) = 42.557		LL(R) > $X_{15}{}^2$ (0.95)		

According to Table 4, evaluation results of digital models show that the value of $\rho_0{}^2 > 0$, confirming the goodness of fit of the constructed mixed logit model. Additionally, based on LL(R) = 1137.738 and $X_{29}{}^2$ (0.95) = 42.557, the likelihood test demonstrates that LL(R) > $X_{29}{}^2$ (0.95), indicating the model's significance at a 95% confidence level.

3.1. Parameter Values

Upon examination of the variable utilities, it was discovered that water features at the rectangular garden stream (garden stream) level ($\beta 12 = 0.490$) and raised planting beds ($\beta 14 = 0.014$) yielded the highest and lowest utilities, respectively. By categorizing the variables into three groups—high, medium, and low utility—it became apparent that water features at the rectangular garden stream level fell under the high utility category (Figure 3, Table 5). High-base lighting ($\beta 5 = 0.314$), crescent-shaped arches (base level), lack of sculptures ($\beta 11 = 0.222$), paving stone–grass pavements ($\beta 8 = 0.169$), concrete fencing (base level) and fountains (base level) were classified as having moderate utility. Natural flagstone pavements ($\beta 7 = 0.109$), metal benches ($\beta 10 = 0.0785$) and the presence of planting beds at the base level had a low utility (Figure 3, Table 5). The other attributes do not reach any ranking in this study.

Table 5. Key findings.

Utility Ranking	Description	Attributes
High utility	The attribute that has the greatest impact on adolescent recovery in an urban park environment.	Garden stream
Moderate utility	The attributes that have a moderate impact on adolescent recovery in an urban park environment.	Light pole high-base Crescent arch No sculpture Paving stone–grass Concrete fence Fountain
Low utility	The attributes that have a low impact on adolescent recovery in an urban park environment.	Natural flagstone Metal bench Raised planting bed

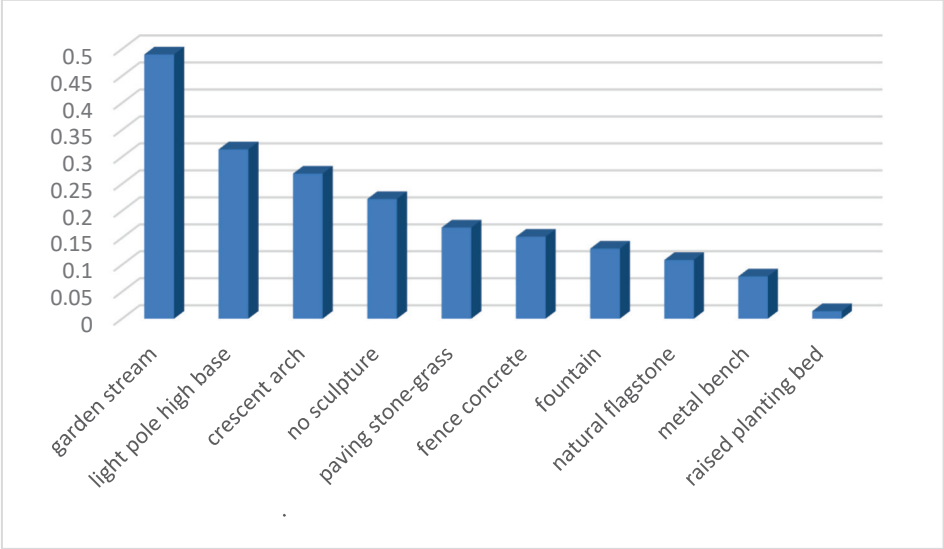


Figure 3. Shows preference of design attributes in 36 digital model based on Table 4.

Participants' preferences were inferred from the sign of the coefficient values. Positive coefficients indicate preferences, while negative coefficients indicate non-preferences. Based on this analysis, it appears that participants preferred the water attribute at the rectangular garden stream level (β12) and the high-base lighting pole (β5) among lighting levels. In cases where negative coefficients were assigned to certain levels, such as the arches (β1 and β2), the base level crescent was preferred by participants. Lastly, when all levels had positive coefficients, as seen in the variable paving (β8 = 0.169 > β7 = 0.109), participants preferred paving stone–grass.

3.2. Random Parameter

Table 4 reports that the mean value was valid for the variables arch and watercourse at all levels, the high lighting, covering with stone–grass material and absence of sculpture (p-value < 0.05). The standard deviation also has an acceptable level of significance (p-value < 0.05). Therefore, there is meaningful heterogeneity between the responses of decision-makers, and the above variables were considered random parameters. However, in the second part of this table, fence at all levels, paving with natural flagstone, and benches with metal material have a significant average effect (p-value < 0.05), but the standard deviation does not have an acceptable level of significance (p-value > 0.05). Therefore, these variables were identified as fixed parameters. Other variables that are presented in Table 4 do not have an acceptable level of significance in terms of mean and standard deviation. Therefore, these variables were determined to be without influence in the experiment.

Additionally, personal characteristics were included as control variables in the mixed logit analysis [51], and socio-demographic factors (age, gender and education) were considered to account for differences in preferences within the study. The model incorporating age and gender significantly influenced heterogeneity among some variables while education did not. The effect of age was significant for the attributes "Paving stone–grass" and "Garden stream". Younger participants (13–15 years) might have different preferences compared to older teenagers (16–19 years). The effect of gender was significant for the attributes "Sculpture" and "Garden stream". This suggests that male and female participants have different preferences for these features.

4. Discussion

The objective of this study was to investigate which design attributes of small, centrally located parks have the ability to create attraction and provide mental recovery to teenagers. Research shows that centrally located parks often have a cultural character. Therefore,

in the selection of attributes and levels, we started from Perceived Sensory Dimensions and PSD Cultural above all. It is defined as containing an essence of human culture—of values of great importance to a people, their values, aspirations, beliefs and hopes [80]. Places that contain this character have proven to be valuable for people in the city because they give people identity and contribute to a sense of place, creating place attachment for personal as well as community mental health [56–59]. Research shows that PSD Cultural is an important health-promoting and restorative characteristic to young people [92,114]. In part, it may be because PSD Cultural gives them an identity and contributes to place attachment [56–59]. In central urban areas, however, PSD Cultural often co-occurs with PSD Social [86], and teenagers have a high need for social activities [56–59]. Stress can be triggered by not having access to social stimulation [115,116]. The results show clear relationships between certain features and the adolescents' estimation of their perceived restorative potential (PRP).

Water features: A clear outcome is that the teenagers prioritize the presence of water in the parks over other attributes. The presence of water features in the digital landscape models indicates the greatest impact on PRP. The rectangular garden stream with flowing water had the greatest impact of the water features, followed by fountains and ponds. It was the only attribute that received a high utility ranking. The rectangular garden stream is a quality closely associated with the Iranian classical garden. It could possibly be that the Iranian background of the participants has influenced this result. It may also be that the Iranian garden's millennia-long history of being a place of relaxation and recuperation [117] has resulted in water having such a prominent place. However, in a study by Wu et al. [118], Chinese youths' recovery from stress, as well as preferences for different attributes, were measured in different urban forests. The results show that water features were a significant predictor of both stress recovery and preferences for specific attributes in urban forests. Dai et al. [38] found in another study that young people rated water elements as being very important in parks. In addition, Rout and Galpern [98] showed that fountains have a positive effect on alleviating the mental fatigue of adolescents.

Several studies on regular park users show that parks and natural areas with moving water are rated as more beautiful than parks and natural areas without moving water. In addition, the moving water is judged to be cleaner and healthier by visitors to urban parks and natural environments [119,120]. According to these researchers, the dynamic and flowing nature of water in rectangular garden streams and fountains creates a greater sense of fascination and visual attraction. According to Professor Richard Coss and colleagues, human interest is easily captured by water, and humans have an excellent ability to judge the quality of water surfaces. This is probably an evolutionarily important trait which has been important for our survival [121,122]. So, perhaps our outcome is not a result attributable to the Iranian nationality of the participants. In addition, numerous studies have highlighted the restorative nature of water in various forms, including ponds, fountains and rectangular water pools [69,101]. Research shows that blue landscapes have a significant impact on improving urban life, promoting peace of mind, improving mental health and promoting social well-being [94,123,124]. Moreover, results show that stays in parks and natural areas with water features are considered to be more psychologically restorative than stays in parks and natural areas without water features. This applies to streams, rivers and lakes, but also artificial ponds and fountains [92,93,117,125].

Lighting: Our results show that young people value lighting on medium-high and above all tall poles. The lighting will, of course, be different depending on the height of the lighting pole in terms of lighting of roads and vegetation, as well as perceived safety [126–128]. In this study, the participants preferred the presence of lighting on high and medium-height lighting poles in the parks, which had a relatively high importance for the recovery potential, in contrast to low lighting poles. This indicates that lighting can have a positive impact on teenagers' recovery and contribute to their overall mental health. Although the study took place in daylight and the question was not about the quality of the lighting—for example, its brightness—this may have influenced the responses.

However, the quality of the lighting is crucial, and the height of the lighting poles plays a big role there. Lyons et al. [20] also found that young people want well-lit parks, which is mentioned in connection with their valuing safety and security. A systematic review by Trop et al. [129] on regular park users showed that lighting in parks has an important and in many cases decisive impact on whether people visit the park or not. It is about perceived safety and it is linked to the quality of the lighting. The lighting must be strong enough for the area to be monitored. If the lighting poles are high enough, surrounding vegetation can also be illuminated. This means that low lighting poles do not provide a sufficient effect. Medium-sized and tall lighting poles are preferable, but not too tall—because then the park is perceived as small and inhospitable. Deng et al. [66] and Rosso et al. [100] have also mentioned tall lighting poles as design attributes, highlighting their positive effects on increased visual comfort, convenience, safety and users' psychological and physiological well-being. Moreover, Peschardt and Stigsdotter [92] confirm the influence of tall lighting poles on perceptions of compatibility, fascination and the feeling of being away. The light pole is a significant physical feature in public spaces, acting as a visual and social component that plays a crucial role in attracting people to the environment and encouraging its use [89]. Users prioritize the presence of high-quality designed lighting poles when choosing and continuously using public spaces [102,103,130]. In addition, lighting poles promote social interaction, sense of fascination and a feeling of being away [92]. The positive effect of lighting as a landscape component to improve people's physical and mental health has also been confirmed [66], and in a study on pocket parks, the design style of light poles was found to be influential in improving comfort and user safety [100].

Arches: The arch, especially the crescent arch, emerged as an important attribute for the teenagers in our study. Dai et al. [38] claim that young people experience parks in a much more multifaceted way than might be expected. Among other things, the sounds and smells in the parks play a big role, as well as the overall structural design and artificial features. Fleckney [21] argues that young people's appraisals of parks, in addition to the expected social and sensory components, also include symbolic and spiritual components. Urban greenways and corridors containing arches are of great interest to regular park users due to their positive impact on recreation, mental well-being and visual aesthetics: they are considered crucial indicators for assessing the quality of life in a city [99]. Wang and Li [83] found that decorative attributes in the form of sculptures, arches, specific works of art and monuments were critical to whether PSD Cultural would have a restorative effect on park visitors. Results by Huai et al. [90] and Huang et al. [91] show that arches especially, as well as sculptures, have a very large impact on whether a park is considered to have good cultural qualities, as well as having good health-promoting, restorative properties. Decorative cultural attributes in the form of arches were also highly appreciated in this study. They emerged as significant attributes, with the presence of this characteristic being preferred over its absence in the park. Specifically, the crescent arch was found to be the most popular among students. This suggests that incorporating an arch, especially a crescent arch, can positively influence teenagers' perceived restorative potential and alleviate mental exhaustion experienced after a long day at school.

Sculptures: The sculpture we added in this study did not work. Researchers indicate that incorporating art features as design attributes has a positive impact on enhancing the landscape's quality on regular park users [102]. When combined with natural features, art features, not least sculptures, increase the restoration potential of the environment [66,96,100,104,105,131–133]. These studies indicate that the presence of sculptures and decorations enhances the attractiveness and coherence of the environment, contributing to both mental and physical restoration and increasing the restoration potential of the environment. Sculptures, as art features and landscape design decorations, play a significant role in the sensory dimensions of the environment and users' preferences. They contribute to improved mental and physical health [92]. Scholars provide evidence of the positive effect of decorations and art features on enhancing adolescent students' health and well-being [134]. In this study, however, the sculpture was more meaningful and effective

when it was absent. The sculpture, as can be seen in Table 2, was a very colorful work of art which stood in stark contrast to the park. The good intention of creating a colorful sculpture that can interest teenagers gives an interesting result here. As it contrasts so harshly with the familiar, it may irritate more than it adds qualities of calm, tranquility and repose. The design aspects chosen here, in terms of shape and color, do not seem to correspond with teenagers' preferences and aesthetics. It may also be the case that exhausted and stressed teenagers cannot bear to face a garish sculpture in an otherwise calm and stress-relieving garden. Another possibility is that the design of the sculpture in a real future scenario, including shape and color, should be brought into dialogue with teenagers to enhance their experiences. Considering students' preferences, culture and aesthetics when choosing sculptures and artworks in a park can significantly influence their preferences and contribute to their well-being and restoration from exhaustion and stress.

Fences: The result shows that the fence is perceived as meaningful and effective for the student's recovery, where the participants preferred the concrete fence. Like Owens [25], several researchers have found that teenagers desire to retreat to more protected places where they can see what is happening in the environment without being seen. They like to retreat somewhat from the city, to something that can function as a shelter [14,15,21,38,135]. Through the ages, a garden has been defined as a piece of fenced land, and the outer wall of the garden is consequently important to how the boundary is shaped. The boundary, which can be a fence or a hedge, helps to demarcate the garden from its surroundings, and if well-designed, it can give the visitor a sense of security [136]. Paradise comes from the old Persian word paridaida, which means walled-around, that is, a walled garden [117]. Fences play a significant role in landscape design. Walls, bushes and trees, commonly utilized as hedges and park fences, have a significant impact on the sense of enclosure and privacy maintenance. They contribute to the feeling of being in a secluded space [48]. A restorative healing garden should be experienced as a place of retreat or haven. An important quality is therefore that it should be possible to experience it as a whole, marked out from the surroundings. In our study, the teenagers felt that the fence must be strong and powerful, made of concrete.

Scholars have emphasized the importance of material selection, color and height of physical elements in parks regarding users' satisfaction levels and ultimately, their restoration [100,103]. The results from Manyani et al.'s [103] studies confirm our results, where they show that fences around visited green areas increase users' preferences for these parks, as well as their feelings of happiness [103]. Nordh's study [48] has also shown that fences and hedges can reinforce the feeling of enclosure and contribute to a feeling of being away. Huang [46] suggests that low-density fences are effective in inviting users and enhancing their enjoyment. Our study and other research therefore suggest that fences and other demarcations of restorative gardens and parks are one of the most influential attributes in promoting health and recovering visitors' mental fatigue and stress. It is also recommended to consider the height and tightness of the fence [46,48,100,103].

Paving: This study showed that all evaluated variants of pavement proved to be both significant and effective. Notably, the teenagers showed a clear preference for paving that contains both paving stones and grass, which gives a softer and possibly more restful impression. Only a couple of studies of teenagers' use of and preferences for urban parks mentioned the paving of the parks, and then, it was not of any decisive importance [35,137]. However, our result is consistent with a couple of studies of regular park users [48,101]. Their results show that the combination of hard surfaces and grass in pavement design improves landscape quality and increases the restorative potential of the environment. As the authors argue, this blend of contrasting attributes provides a harmonious balance and offers visual appeal, capturing students' subconscious attention and promoting increased fascination and restoration. In addition, Peschardt and Stigsdotter [92] emphasized the importance of considering roads as a social aspect of design, given that the choice of pavement material can significantly influence user preferences, thereby increasing fascination

and ultimately facilitating the restoration of attention. Consequently, the selection of appropriate pavement materials has great importance to promote environmental harmony and upgrade the physiological and psychological well-being of users [66]. The floor of the restorative garden, which to an important extent consists of paving, is also of great impact regarding the quality of recovery [137]. Several studies have shown that material selection and its design in pavement construction can significantly affect the general well-being of park visitors [100,138].

Bench: Our results regarding the bench design indicate that although users prefer its presence, its effectiveness and significance levels are relatively low. It seems that benches satisfy students' need to take a break, relax and reflect. A number of studies mention that seating is a relatively important feature of urban parks for teenagers in terms of resting, as well as participating in social activities, although it is not mentioned as having decisive importance [14,19,21,137]. In several studies of regular park users, however, park bench design has been considered a priority for park users and has been shown to have a positive effect on overall preferences and stress reduction [33,72]. Manyani et al. [103] argue that attributes such as park benches are directly linked to increasing users' sense of enjoyment, happiness and overall positive experiences in public urban green spaces. Regarding the aesthetic value and restorative properties of park benches, Pals et al. [95] found in a study in the Netherlands that wooden furniture had a higher effect than metal furniture in increasing user preferences, enjoyment and restoration from high stress levels in natural environments. In contrast, our results show that the teenagers prefer metal benches over wooden benches, which may be due to cultural norms and user preferences, which Wang and Yoon [97] suggest should guide the choice of park furniture design. According to Manyani [103], the availability of benches is a key factor in users' choice of parks, contributing to their overall satisfaction and enjoyment. A study also showed that teenage students tend to choose benches near fountains and in sunny areas because of the positive feelings they evoke [98]. Therefore, it would be worthwhile to further explore the design of park benches and their placement in future studies.

Planting bed: Contrary to previous studies, our results suggest that the presence of the raised planting bed attribute did not significantly influence adolescent students' choices. Van Vliet et al. [137] found that the presence of planting beds in particular, especially with a diversity of species of flowers, influenced teenagers' preferences for parks positively. Nordh et al. [69] evaluated the presence and absence of planting beds regarding their restorative effect on regular park users. The results indicate that planting beds have a high value and have good restoration potential in small urban parks. Other studies have confirmed these results [66,103,139]. Although the results of this study indicate limited influence of the planting bed on students' choices, it is possible that this feature contributes to the organization and cohesion of the landscape, thereby influencing its visual appeal and capturing the unconscious attention of teenagers. A fact that can affect the result is that the raised planting beds were designed to be so low that they could most likely be perceived as plant bed edges. Therefore, modifying the design of the shape, material and color of this attribute may increase its effectiveness in terms of perceived restorative potential and its impact on adolescent choices.

Strengths and Limitations

The strength of this study is that it uses discrete choice modeling, which is the most recently applied technique in the health field. The discrete choice method has several advantages, as it allows the estimation of marginal utility. Each option consists of a combination of different function levels. This method allows researchers to explore individuals' values and priorities regarding the desired characteristics of, in this case, small, centrally located parks [140].

In addition, this study incorporates visually visible features by providing participants with digital and designed color photographs. Studies show that exposure to realistic natural environments gives participants opportunities to experience health-promoting

properties [70]. Moreover, the choices offered in the discrete choice method are closer to the traditional individual decision process [140].

However, this study has some limitations: the instructions for perceived restorative potential differ from, e.g., Twedt et al. [77] in this study. While the study by Twedt [77] mentioned "overwhelmed, stressed, tired, and anxious", our instructions mentioned "mentally tired". Our choice was about getting the students to imagine a concrete, everyday situation where a visit to a park can make a difference. If the students can give a well-thought-out choice of a place that is judged to give the most rest, it probably conveys at the same time that the place provides stress relief, calmness, connection and regaining of attention capacity. Consequently, we judge that the recovery should be explainable on the basis of several theories.

Second, the use of image-rated online surveys may not accurately capture user preferences. Because this specific knowledge gap is unexplored, in an initial study, we need to reduce all confounds and interferences. If we were to conduct the study in a real environment, the weather, time of day or year would likely have an influence on the results that would be difficult to control. Several carefully conducted studies show that participants in research studies are good at interpreting images. The result from images with real environments is in good agreement [141,142]. In addition, the objects we wish to study need to be simplified to what is truly typical of what they represent, as a kind of symbol. However, the use of image-rated surveys may not accurately capture user preferences. We suggest that future projects should verify our results through studies in real settings, determining if small centrally located parks with the characteristics proposed in this study have a beneficial effect on teenagers' mental recovery. In these studies, for example, measurement of recovery via salivary cortisol, skin conductance and HRV can be used as a complement to self-rating scales.

Third, in this study, we achieved very good contact with private schools that were happy to participate in the study, while unfortunately, we did not obtain any contact with public schools. In a future study, we will make more of an effort to include public schools. In addition, there were approximately equal numbers of male and female students attending the schools included in our study, but more girls chose to participate. Age, gender and education need more detailed studies. The purpose of this article was not to examine them. Therefore, future studies should investigate this more thoroughly.

5. Conclusions

All over the world, there is a need to improve the mental and physical health of teenagers. Not least, they suffer from stress and mental exhaustion. An increasingly clear amount of research evidence shows that visits to urban parks can lead to recovery from high stress levels and from attention fatigue. Research shows that teenagers do not need special parks and green spaces of their own. On the contrary, urban parks that are visited by all should be developed so that they are also used more and work better for teenagers.

Research shows that teenagers like to visit urban green spaces in the most central parts of cities. This study focused on this type of urban green space, where 250 teenagers evaluated different digital models. The result shows that the biggest impact on the recovery is that the content is characterized by water, where the rectangular garden stream stands out. The area should also be well lit and separated from the surroundings. Moreover, it should include attributes that show it has an important cultural function, such as an arch, fountain and planting beds. The whole area should give a soft impression, such that the pavement consists of paving stones and grass, and the park contains a soft crescent arch. In conclusion, this research highlights the need for requested attributes such as larger flowing garden streams, arches, lighting and planting beds, which require investment and good maintenance but can result in greater benefits and advantages, as they meet the needs of users and contribute to their overall health and well-being.

Similar to some other studies, e.g., [19,98,137], whether presenting digital or natural models, we report that the design of physical facilities such as benches, ponds and paths

together with natural features such as flowers and trees in parks can recover young people from high stress levels or mental exhaustion. If urban environments obtain these qualities, they should have the potential to act as attractive health promoters for teenagers. However, the central parts of cities, where teenagers are often attracted, too often lack green areas with attractive and health-promoting qualities.

To create inclusive and accessible spaces that promote physical and mental well-being, social interaction and community engagement, park designers and urban planners must consider user preferences, culture and aesthetics. The design and maintenance of urban parks is critical to creating a health-promoting and restorative environment that benefits the overall health and well-being of park users. However, to achieve a more precise understanding of this topic, further research is necessary. Future studies should investigate whether small centrally located parks with the characteristics suggested in this study have a good effect on mental recovery in randomized controlled trials. In these studies, e.g., VR equipment, AR technology, eye-tracking and measurement of recovery via salivary cortisol, skin conductance and HRV can be used as a complement to self-rating scales.

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Smart Street Furniture: User and Non-User Perspectives of the ChillOUT Hub

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Abstract: This article addresses gaps in knowledge about whether or not smart street furniture could enhance the relationship between people and place, and whether it improves the design, amenity and management of public open space. An Australian design team, comprising a local council, a street furniture manufacturer, and academics, designed, built, piloted, and assessed a new piece of smart street furniture called a 'ChillOUT Hub'. This Hub is an integrated street furniture system, designed for public open spaces. It is enabled with 'smart' technology features such as Wi-Fi, mobile device charging stations, plus infrastructure usage and environmental sensors. The Hub aims to support social health, improve microclimatic conditions, and provide equitable access to technology. Street survey processes were undertaken with both 'users' and 'non-users' of the Hubs. The findings help to identify what value digitally enhanced street furniture actually has in open space and how that value is perceived by the public. The Council and Hub users overwhelmingly appreciated the newly designed street furniture and its smart amenities. Non-users clarified why they did not use smart street furniture and discussed the option of having digital amenities in public spaces more generally.

Keywords: smart street furniture; place; smart cities; public space design; public realm; ChillOUT Hub

1. Introduction and Context

Considerable research on plazas, streetscapes, and parks has shown that successful public places are functional, inviting, cared-for, and well-used [1–3]. Specifically, "successful public spaces are ones that are responsive to the needs of their users; are democratic in their accessibility; and are meaningful for the larger community and society" [4] (p. 1). In the context of the COVID-19 pandemic and its aftermath, the social and physical value of public spaces has grown. Smart public spaces are increasingly being offered, which include outdoor work and play spaces of the future with the thoughtful provision of 'smart' or digitally enabled infrastructure [1]. However, such attributes "must be coupled with metrics and methods of understanding how people behave and use these spaces to be meaningful in evaluating how "successfully" they are being used" [1] (p. 99).

This article addresses gaps in knowledge about whether or not smart street furniture enhances the relationship between people and place and has the potential to improve the use and amenity of public space. As part of the 'smart cities' movement, planners and other city designers are using their public realms to test innovative ideas for collective learning [5] and creating 'smart citizens' [6] by default. Exploring and developing solutions in 'living labs' "is extremely powerful because it suggests that experimental attempts, ideas, observations, results, failures, and successes all belong to a collective learning process . . ." [5] (p. 36). This collective learning turns into capabilities in the private and

public sector which further enables the ongoing use of smart technologies for the design and performance of public spaces [1].

In this context, this article represents a public evaluation process completed on a newly created street furniture product enabled with 'smart' technology. The 'ChillOUT Hub' provides traditional functions (such as seats, tables, shade, and water) combined with digital features and connectivity. This article presents and analyses the results from two 'on-the-street' survey processes which provide perspectives from those who do and do not use smart street furniture; why these new micro-infrastructures are used; and how they can be improved. The final discussions highlight, through survey metrics, what value digitally enhanced street furniture actually has for people and how that value is perceived by both the public and the Council.

1.1. Smart Cities, Smart Technologies

The smart city movement "is the latest urban movement to use digital knowledge, applications, and innovation for the benefit of processes, people, and place" [7] (p. 4). A smart city (sometimes called a digital city) is "a high-tech intensive and advanced city that connects people, information and city elements using new technologies in order to create a sustainable, greener city, competitive and innovative commerce, and an increased life quality" [8] (p. 135). A smart city often uses data collection sensors, big and small data sets, geographical information systems, virtual reality (VR), artificial intelligence (AI), digital platforms, and the 'Internet of Things' (IoT) to respond to key urban challenges and connect urban services with stakeholders [9,10].

An IoT system can enable rapid municipal action through automated data collection for evidenced-based decision-making and asset management [11]. For example, smart benches can provide visitor tracking data, solar-powered device charging, and Wi-Fi hotspots, while sensor networks and the IoT can be used to automatically program public space features. Digital sensors can "record, store, and wirelessly transmit information about light intensity, temperature, moisture, air and water quality, resource consumption, motion, and other factors" [12] (p. 220). Multiple sensors can be linked together to create an IoT network that collects data over a wide area that is beneficial to urban space managers. Ten years ago, Stankovic [13] (p. 4) stated from a technological perspective, that IoT systems would become "a utility with increased sophistication in sensing, actuation, communications, control and in creating knowledge from vast amounts of data . . . result[ing] in qualitatively different lifestyles from today". Upon reflection, Stankovic was right in his predictions.

Beyond technological enhancement, the smart cities movement can also benefit place design, planning and management. A smart city can create "efficiencies in systems, infrastructure, and soft services; [provide] data-driven evidence for decision-making" [14] (p. 185); improve community health and well-being, and thus quality of life [15]. Technology embedded in places can facilitate people's encounters and change their relationship with it. However, opposing views caution that "urban informatics will need to be used thoughtfully and ethically" [14] (p. 185) and that, "technology-pushed solutions have often failed to engage either citizens or the public authorities who provided them" [9] (p. 198).

1.2. People–Place Relationships and Smart Street Furniture

Public spaces are essential to fostering social interaction, providing a place for public life, and improving a city's quality of life with different place dimensions [16]. Street furniture, specifically, can exert both active and passive influences on the design of urban space and, consequently, "on the relationships between people and place in urban environments" [7] (p. 1).

Street furniture is defined as micro-infrastructure that includes signs, benches, parking meters, trash cans, water fountains, bollards, streetlights, or "anything at human scale that increases the complexity of the street" [17] (p. 12). Apart from its main function, providing human-scale amenities to improve that place, street furniture can also make residents and

visitors feel safe, acknowledged in history, belonging to the community, and considered in the design of their public spaces.

Urban design generally, and streetscape features, such as street furniture, more specifically, "have a significant influence on pedestrian activity" and the activation of public spaces [17] (p. 12). Seating is key to welcoming places because it "invites passersby to visit, linger in, and enjoy public spaces in ways that activate our public and civic lives" [18] (p. 13). It creates opportunities for resting, sitting, eating, and social encounters, and may also be of functional importance to the elderly, those with limited mobility, and adults with young children. Benches and tables in parks and squares can also be socially significant as they create "a comforting and appealing air and draw people in" [19] (p. 624), and "stimulate social encounters and encourage people to talk to strangers" [19] (p. 625). These should be co-located with other amenities "where there is protection from the wind and to allow a choice of sitting in the sun or shade" [19] (p. 628). Shade structures are particularly relevant as a basic heat mitigation strategy, in increasingly hot cities [20].

Cities are increasingly offering next generation infrastructure [1]. By linking street furniture to public carriers or IoT networked cities, they can offer new services for citizens and visitors in the form of Wi-Fi, mobile charging, interactive maps, and real-time event information and alerts. In addition, cities can gather environmental (e.g., temperature, air quality, noise) data from sensors on smart street furniture to manage factors that affect neighborhood health and safety [21]. In a public transport setting, smart bus shelters, e-bike sharing, and electric vehicle charging stations can be gathered alongside other street furniture to create a multi-purpose hub.

Smart kiosks, tech-enabled poles, and smart benches (like the Steora bench—Croatia and the Strawberry bench—UK) have only been mass produced in the last five years and now provide innovative combinations of street furniture and digitally enabled Information and Communications Technology (ICT). A defining feature is that they "combine and recombine functionalities that exist in prior urban forms—like benches, public pay phones, Wi-Fi hotspots and charging stations, wayfinders, and advertising billboards" [22] (p. 3).

Wi-Fi is increasingly important for people's experience of the city, especially for individuals who rely heavily on public connectivity, such as youth, delivery riders, and those, like the homeless population, who lack, or have limited, home Internet services. [22]. Further, an increasing number of people are mobile during the day. Many of them make use of personal electronic devices for working, studying, or leisure activities, and need to use these devices outdoors, especially during breaks between daily activities [23]. Adding these features in public spaces increases accessibility and provides a means for civic participation, helping to reduce the divide in digital inclusion [23].

Gouvea and Mont'alvão [24] (p. 556) remind city designers, that the place where smart street furniture is installed must be "intentional and conscious . . . in a way that all objects together can exploit to the maximum each object and its functions". Fang et al. [25] (p. 1375) go on to suggest that the "need to rethink the smartness of smart cities is appropriate to each city based on its culture, people's needs, economic development, and other factors".

1.3. The Need for More Research

Some researchers have suggested that the quality of pedestrians' user experience has not been adequately investigated [26], and there is little research on the needs and preferences of pedestrians regarding street furniture [21,27], especially smart street furniture. A rare exception is the recent work by Wessels et al. [22], who tried to capture, qualitatively, through Vox Pops, "the awareness of smart street furniture in specific locations by people who were in one of the sample locations at the time, their perceptions of this new type of furniture and of their benefits and disadvantages, as well as their uses (or lack thereof)" [22] (p.11).

These calls for more research demonstrate the existence of relatively few studies on smart street furniture as this is a new area of product design and its interaction in public space. This body of literature is starting to grow: Nassar et al. [10] documents how smart

street furniture is featuring in cities as they increasingly become smarter. Premier et al. [28] show how solar power is making smart street furniture more sustainable. Other researchers are looking at different applications of smart technology such as APPs, AI, and VR, which can be used in the design of public space [6,12,29]. The authors, an Australian design team which invented a new smart 'ChillOUT Hub', also hypothesized about who might become users of smart street furniture, who would not use it, and how this new type of micro-infrastructure might alter the public realm. The following section discusses the design, delivery, and assessment of the ChillOUT Hubs.

2. Research Design and Method: ChillOUT Hubs: A Case Study

The production of public space is increasingly reliant on cross-sectoral alliances. Public–private partnerships (like this case study) are an increasing trend in city planning, place-making and design [12]. Collaborations can be mired with challenges such as differing resources, knowledge, and ultimate goals. However, innovation and knowledge exchange across the sectors can create rich, diverse, and very productive environments, whereby the work has a huge impact on the outcomes for people and place in cities.

The ChillOUT Hubs are the result of a multidisciplinary and multi-sectoral project entitled 'Smart Social Spaces: Smart Street Furniture Supporting Social Health'. The tripartite collaboration included Georges River Council (a local government area in the Sydney metropolitan basin), Street Furniture Australia (a private company), The University of Sydney, and UNSW Sydney. The aim of the research was to design a piece of new, tech-enabled street furniture, test it in a 'living lab', and evaluate it from the view of the public, which is reported on throughout this article.

The purpose of a ChillOUT Hub was to offer a redesign of public space to include digitally enabled smart street furniture, creating flexible places to meet, work, and play. In addition to providing standard street furniture functions, it was important that the Hubs offered free Wi-Fi, mains and solar power, ambient lighting, and USB charging points. The 'smart tree' shade structure aimed to create 'cool spots' to combat rising urban temperatures. Co-located infrastructure at the Hub locations were also turned 'smart' and tested in situ to document how different smart technology would be perceived in a diverse, high-density community. Sensors to count the number of users, capture local environmental conditions (wind, precipitation, temperature, humidity), and track power and water usage were added. An IoT network of these sensors transmitted live open-source data about the microclimate, use of the Hubs, and performance of the public furnishings to a Council dashboard for smart asset and place management.

The Hubs are designed as a modular system that can be customized by location and need. Three project sites across the Georges River Council area were selected to pilot test the Hubs. They were placed in three different communities, all within the same local government area (Georges River Council): (1) Kogarah is the community in which the Belgrave Street Hub was sited. This project site lies on a main pedestrian thoroughfare adjacent to a small plaza, a public library, church, residential buildings and local stores. The project site is located a few minutes away from a train station and a hospital. (2) Mortdale is the community in which the Macquarie Place Hub was sited. This solar-paneled Hub took over a section of road and footpath which is next to a local shopping strip embedded within a residential neighborhood. (3) Hurstville is the community in which the Timothy Reserve Hub was sited. This Hub is in a park adjacent to a major sports oval located within a residential area. Table 1 indicates important considerations for the siting of the Hubs.

The diversity offered across these three communities also offered an important opportunity to explore people's behaviors in relation to the Hubs in three different open space typologies (a plaza, a streetscape, and a park). Figures 1–3 show each of the three sites before and after the installation of the Hubs.

Table 1. ChillOUT Hub site communities.

	Population	Density (Persons per Hectare)	Open Space Typology for the Hub
Kogarah community	7197	78.11	urban plaza
Mortdale community	11,178	38.75	streetscape
Hurstville community	25,013	69.31	park

Data source: Profile.id 2020 [30].



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

Figure 1. (**a**,**b**). Belgrave Street, Kogarah, without and with a ChillOUT Hub. (Photographs by Nancy Marshall).



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

Figure 2. (**a**,**b**). Macquarie Place, Mortdale, without and with a ChillOUT Hub. (Photographs by Nancy Marshall).



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

Figure 3. (**a**,**b**). Timothy Reserve, Hurstville, without and with a ChillOUT Hub. (Photographs by Nancy Marshall).

Research Design and Methodology

Based on the local community demographics shown in Table 1, 385 completed questionnaires were needed for both 'users' and 'non-users' (conducted across three ChillOUT Hubs) for the survey results to have a 95% confidence level and a +/− 5% margin of error [31].

Using an intercept survey technique, 424 questionnaires were completed by ChillOUT Hub *users* across the three pilot sites, and 460 were completed by *non-users* (those who passed by the Hubs without stopping). Both surveys were conducted over four months (December 2019 to March 2020) on weekdays and weekends, at three fixed-time periods in the mornings, afternoons, and evenings. The six-person trained survey team included English, Mandarin, and Arabic speakers who could interpret questions for participants as required. Due to the significant proportion of people with Chinese ancestry in the area (28%) [30], both surveys were translated and available in Mandarin. The survey instruments were written using plain language for ease of understanding in both the English and Mandarin versions. No technical or complicated design terminology was needed in either survey.

Table 2 shows the spread of questionnaires completed at each Hub site. All data were entered into the statistical package SPSS as it was collected. Data cleaning and control was performed regularly to ensure the integrity of the data set. All frequency tables and key cross-tabulation data shown are sourced from the original research and rounded to the nearest whole number. This research had formal UNSW Human Research Advisory Panel ethics approval.

Table 2. Surveys completed at each ChillOUT Hub site.

Survey Sites	Hub Users	Percentage	Hub Non-Users	Percentage
Belgrave Street (plaza)	136	32%	145	31%
Macquarie Place (street)	138	33%	150	33%
Timothy Reserve (park)	150	35%	165	36%
Total	**424**	**100.0%**	**460**	**100.0%**

The User Survey was delivered as a 'person-on-the street', self-administered questionnaire, conducted as a person was using one of the three Hubs. The demographics of the user respondents are presented in Table 3. The surveyors remained close by to clarify any questions or concerns. The aim of the User Survey was to document their experience using the Hub and to obtain their evaluation of this smart furniture in public space. The survey was structured into four themes to capture these data:

- Theme 1. Hub Use: The main reasons for using the Hub, the frequency and duration of use, whether it was used alone or with others, and willingness to use the Hub in the future.
- Theme 2. Hub Features: Evaluation of the location of the Hub, its physical features, and the amenities and technologies that might improve it.
- Theme 3. Hub Value: The experiences of Hub users related to thermal comfort, safety, their sense of energy and well-being when using the Hub, and their overall satisfaction with the Hub.
- Theme 4. Demographics of the Survey Respondents.

The Non-user Survey was designed to have surveyors ask the questions and record the answers, although respondents could complete the questionnaire themselves if preferred. The demographics of the user respondents are presented in Table 4.

Table 3. User Survey Respondent Demographics.

Gender	53% male; 46% female; 1% not stated
Age (years)	20% 18–24 yrs; 36% 25–39 yrs; 27% 40–64 yrs; 15% 65–79 yrs; 2% 80+ yrs
Residence	67% Georges River Council; 30% Sydney basin; 2% outside Sydney
Employment Status	30% full-time; 24% part-time; 19% retired; 13% student; 6% unemployed 5% other

Table 4. Non-user Survey Respondent Demographics.

Gender	54% male; 46% female; 0% not stated
Age (years)	9% 18–24 yrs; 39% 25–39 yrs; 30% 40–64 yrs; 18% 65–79 yrs; 2% 80+ yrs
Residence	69% Georges River Council; 30% Sydney basin; 2% outside Sydney
Employment Status	41% full-time; 22% part-time; 21% retired; 7% student; 6% unemployed 4% other

The aim of the Non-user Survey used the following three themes to document why the Hub was not used and to collect broader needs and preferences for future designs of both smart street furniture and technology in the public realm.

- Theme 1. Hub Use: Reasons the ChillOUT Hub was not used, the frequency of passing the Hub, the value of the ChillOUT Hub as a social space for the community, and their willingness to use the Hub in the future.
- Theme 2. Future Designs and Technologies: Hub features that might be used in the future, the value of having smart street furniture in any public open space, and preferred technologies to be available in public open space.
- Theme 3. Demographics of Non-Users.

It is important to acknowledge the limitations of this survey process. Firstly, the surveys began just one month after the installation of the three ChillOUT Hubs. Thus, their evaluations of Hub use or features may have been different if recorded at a later date. Secondly, restricting survey participation to adults meant that children under the age of 18, who often use smart technologies, could not evaluate and provide feedback on the Hubs. The Survey was conducted before COVID restrictions on public space were enforced. As the ChillOUT Hubs are still in full operation, this research could be repeated to analyze the 'normalized' use and non-use of the Hubs.

3. Results

3.1. Reasons for Hub Use

As shown in Figure 4, the top reason given for using a ChillOUT Hub was because people needed a seat or were resting (26%). For others, it was a social space, used as a meeting place to wait for others (17%) or having a meal or coffee (14%). Whatever else they were doing, 17% of respondents were also using the Hub's smart technologies, specifically charging a phone (9%) or using Wi-Fi (7%). Cross-tabulations revealed that more females than males used the Hub for having meals or coffee, but more males used the Hub for charging a phone and using Wi-Fi. Others were 'just trying it out', studying or working (4%), or using the co-located smart water fountain (4%).

Just slightly more people use the Hub with other people (their family—25%; friends—22%; and work colleagues 5%) than those who use the ChillOUT Hubs on their own (46%). Only 2% are there with their pet. An overwhelming majority of Hub users surveyed indicated they would use the Hubs again (95%).

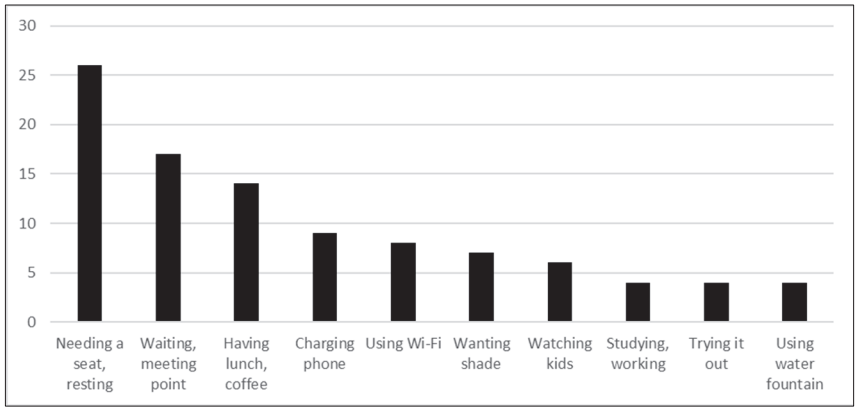


Figure 4. Users' reasons for using ChillOUT Hubs.

3.2. Frequency of Use

Well over one-third (39%) of ChillOUT Hub users indicated they were using the Hub for the first time. A further 13% used it less than once a week, 18% used it once a week, 22% used it two to six times per week, and 8% used a Hub seven or more times per week, suggesting multiple use on certain days. Cross-tabulations revealed that more people over 40 years of age visit a Hub two or more times per week than do younger cohorts. Somewhat surprisingly, it was not the first visit to a Hub for almost half of respondents who lived outside the local government area.

3.3. Duration of Use

When length of stay was examined by site, the most common duration across all three sites was 10 to 30 min, as shown in Figure 5. It was uncommon for people to stay for more than one hour at the ChillOUT Hubs located in Belgrave Street and Macquarie Place, both of which are near commercial areas. However, one-fifth (19%) of Hub users in Timothy Reserve stayed for more than an hour, likely due to its location in a park with nearby opportunities for intergenerational recreational activities.

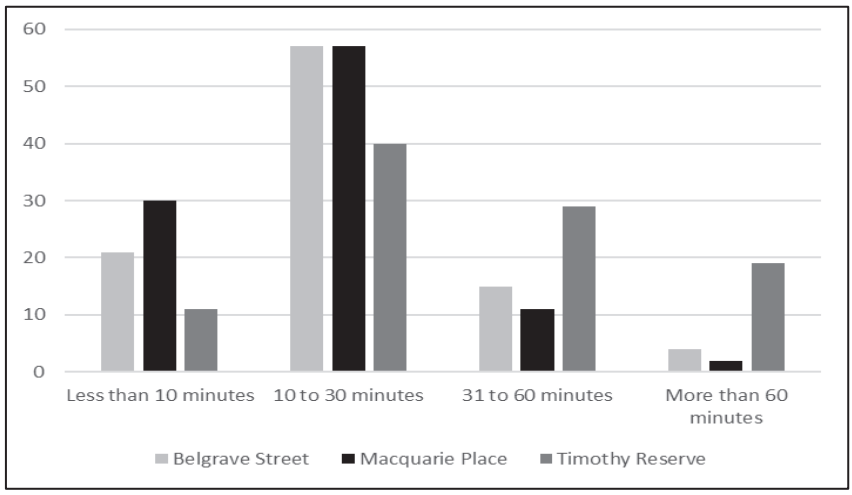


Figure 5. Users' average length of stay at each ChillOUT Hub site.

Among respondents whose main reason for stopping at a Hub was to have lunch or coffee, most stayed for 10 to 30 min, as did those who were charging their phone. Among those who used a Hub to study or work, the majority stayed up to an hour. Just over half of respondents who wanted shade used a Hub for 10 to 30 min.

3.4. Top Amenities Used

The top three amenities used across all three sites were seating (27%), tables (24%), and shading (16%). Respondents (one-fifth) also made use of the smart technologies provided, specifically Wi-Fi (9%), charging a phone (7%), or using a power outlet (4%). A further 9% of respondents used the Hub's co-located smart garbage bin. The smart water fountain, a feature provided only in Timothy Reserve, was used by 6% of all users. Cross-tabulations revealed that more females than males used the available shading at the ChillOUT Hubs, whereas more males used smart technologies. When employment status was examined, the use of all smart technologies combined was greatest among students (28%), those employed part-time (21%), the unemployed (17%), retired people (16%), and those employed full-time (15%).

3.5. Reasons for Not Using a Hub

As shown in Figure 6, the top reasons non-users gave for not using a ChillOUT Hub were that they were busy (34%), they did not notice the Hub (21%), or the weather was too hot, cold, rainy, or windy (9%). Non-users also expressed uncertainty about what the Hub offered (7%) and gave a variety of reasons (e.g., poor location, crowding, not for kids, not free, not clean, or safe, and not private), which together accounted for 7% of responses. However, almost one-quarter of non-users provided 'other' reasons for not using a Hub: almost half of them said they did not live in the area or did not come to this location often and nearly one-quarter noted there was no shade at the time they passed the Hub. A few others said they did not stop because they were walking a dog, looking after their kids, or lived nearby and were going home.

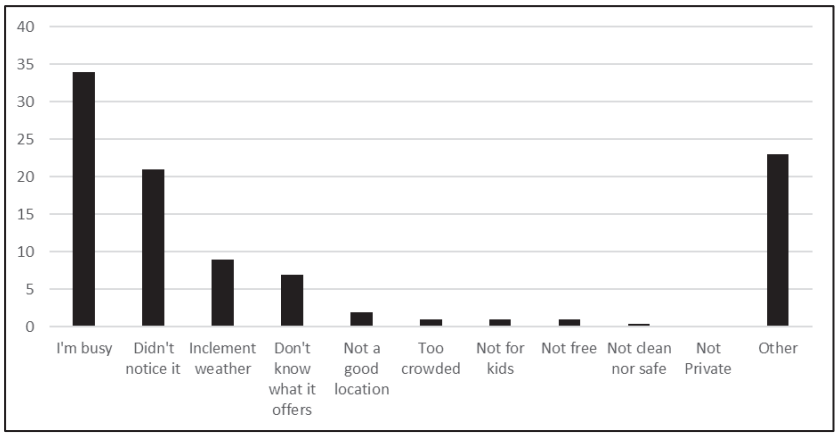
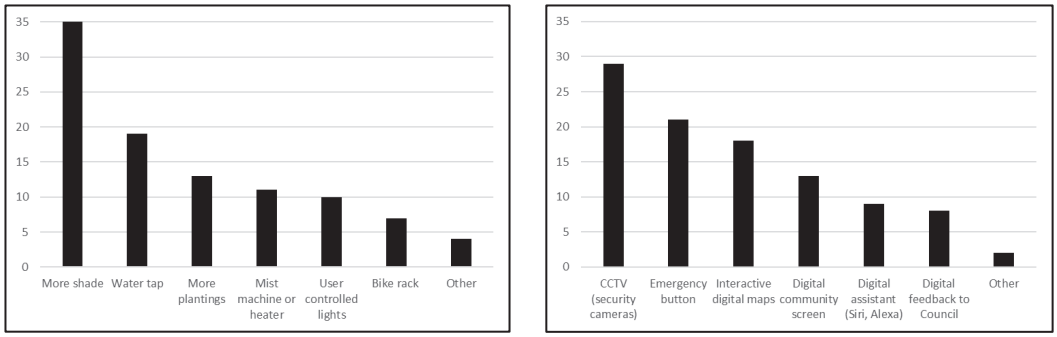


Figure 6. Non-users' reasons for not using the ChillOUT Hub.

3.6. Desired Amenities

Regardless of whether respondents were users or non-users of the Hub, all were asked about the positive and negative aspects of having smart street furniture in that location. User respondents were asked to rank amenities that might improve the ChillOUT Hub they were actually using. As shown in Figure 7a, across all three sites, people wanted more shade (35%), a water tap (19%), likely since there is no water access at two of the three sites, and more plantings (13%). These were followed by a smart misting machine for summer or a heater for winter (11%), controlled lights (10%), and a bike rack (7%). A variety of other suggestions were made by 4% of users, including benches with back supports, chairs for kids, and cigarette bins. Cross-tabulations revealed that Hub users aged 65 to 79 ranked 'more shade' in their top three preferred amenities more frequently than all other age groups, followed by respondents aged 18 to 24. Respondents aged 18 to 24 and those aged 65 to 79 also ranked 'more plantings' in their top three preferred amenities more often than other age groups.



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

Figure 7. (**a**,**b**). Users' ranking of amenities and technologies to improve ChillOUT Hubs.

Non-users suggested that more smart garbage bins, additional solar panels, seats with backs, retractable shade screens, and a toilet could be added to the Hubs.

3.7. Desired Technologies

Users were asked to rank specific digital technologies that might improve the ChillOUT Hub they were using. Shown in Figure 7b, the top choices across all three sites were security cameras (29%), an emergency button (21%), and an interactive digital map (18%). Both females and males ranked security cameras almost equally in their top three new priorities for the ChillOUT Hubs, but more females ranked an emergency button as a top priority. Security cameras were more of a priority for Hub users aged 65 to 79 and 25 to 39. Adding an emergency button was more of a priority among those aged 65 or older. Digital maps were a much higher priority for respondents aged 18 to 24 than for all other age groups and were a top priority for males.

When non-users were asked which technologies they would like to see in public open places, their top choices were public Wi-Fi (20%), user control of shade structures (18%), phone charging stations (17%), and security cameras (17%). Interestingly, Wi-Fi and charging was available at the Hubs.

3.8. Overall Value of the Hubs in the Public Realm

ChillOUT Hub users were asked whether the Hub was valuable as a social space. Almost all users (97%) thought the Hub improved the local area and most (93%) indicated the Hub made them feel they were part of the community. A significant majority (84%) of non-users indicated they would use the Hub in the future.

When respondents were asked if they would like to see Hubs in other places, 93% of ChillOUT Hub users said they would. Their top three preferred locations were parks (24%), urban plazas (17%), and street corners (13%), which were also the top three choices for non-users. Hub users then preferred beaches (11%), bus stops (10%), and hospital grounds (10%), which non-users placed in the reverse order. Both users and non-users selected sports grounds and school grounds as their bottom two choices for new Hub sites.

Throughout the paper we have indicated variation in use and non-use based on demographic data. At this stage there are no greater generalizations to make beyond this in relation to our hypothesis. This type of smart micro-infrastructure is still rare, and the social patterns of use and non-use are still emerging. However, it is already clear that smart micro-infrastructure has broad appeal across demographic characteristics and that the potential of its opportunities are well recognized by the community. It has the potential to alter the public realm by activating another (technological) layer, and means to provide for community engagement and opportunity which is accessible to all.

4. Discussion

This research examined how smart street furniture could enhance the relationship between people and places, and whether it improves the design, amenity, and management

of public open space. It was a test, inserting smart technology into public spaces to help city designers and asset managers decide if 'more or less' smart technology should be in public space, especially in the form of street furniture. The ChillOUT Hub was a pilot test set up to address these research questions. Would smart street furniture ultimately enhance people's use of technology-enabled public space or deter them from using it?

Users' Perceived Value: First and foremost, both users and non-users of these ChillOUT Hubs recognized their value in the public realm. The general public acknowledged the intersection between the technological Hub with social interaction, safety, and well-being, and their engagement with technology, in general, in public space.

The feedback from Hub users reveals their experiences using a ChillOUT Hub and their evaluation of its amenities and technological features. The perceived value of the ChillOUT Hubs is statistically remarkable, considering two-fifths of survey respondents were visiting the Hub for the first time and many others had become regular Hub users just within a few months of a Hub's installation. Addressing the hypothesis about improving location amenity, almost all users (97%) thought the Hub improved the urban space and 84% of non-users suggested they would use the Hub in the future.

Council's Perceived Value: Supported by several experts and studies [10,26,29,32], Kher Kaw et al. [1] (p. 102) states that these types of "urban technology (urban tech) applications for streets provides a glimpse into how streetscapes might change in the future". The design, management and use of public open space is evolving. Livable cities can adopt different open space provision models and maintenance strategies [1]. These cities can support small, organic, temporary, and low-impact approaches to make changes in public space, or take a more top-down approach with more permanent structures, at a larger scale, and perhaps have a larger impact. This research has documented the process of a council that took a top-down approach in the site selections, the motivations behind the Hubs and in the delivery of the Hub concept (with support and expertise from a design team). Despite the lack of involvement by the public in the planning process, the community has welcomed the Hubs, and the investment by the Council in its open spaces and commitment to its local residents.

"Because public spaces are mostly municipally owned and managed, local governments can exert a substantial influence on cities' urban environment. Specifically, small improvements to public spaces could catalyze an important process of urban transformation" [1] (pp. 7–8). The ChillOUT Hubs revitalized small spaces in the local urban fabric. They also contributed to the Council's larger smart agenda and its own capacity to deliver smart projects for community benefit. The Hubs were not included in public spaces as a larger renewal or place-making strategy or even to increase commercial activity nearby.

The motivations behind the design of the Hubs and their site selection were that they could contribute to Georges River Council's focus on urban heat mitigation, particularly topical for Australian public space management. Equitable access to free Wi-Fi and other technology in public space was also important to the Council in the co-design stages of the Hub. The smart social space was designed to be human scale and 'low intensity,' for local residents' use, and to have a small footprint. Since piloting the three ChillOUT Hubs, the Council has installed several more of these. The Hubs are now a commercial product called a ChillOUT Tree manufactured by Street Furniture Australia. The ChillOut Tree has modified specifications and smart features [33].

In Australia, smart street furniture, also becoming known as 'street furniture with electronics' [33], is bound by the same International Organization for Standardizations (ISOs) and product certifications relevant to the production and sale of traditional street furniture. From a council perspective, rarely are any special permits or licenses required to put smart street furniture in the public domain. Once a product is installed, the custodian (or owner of the asset) is responsible for maintenance of the electricals unless it is a warranty case—at that point it would be the furniture supplier's responsibility to make repairs or replace the componentry.

Social Interaction: More than just providing new amenities, ChillOUT Hubs were immediately perceived as a social opportunity by the community. As William Whyte [34] (p.19) stated from his work in city plazas in the 1970s, "what attracts people most, it would appear, is other people". Four decades later Gehl [3] also acknowledged people's need for social contact and the power of the potential of this in people's use of the built environment.

Attributes of the built environment, when assembled sensitively and with the community in mind, often transcend their particular function and galvanize new and much more significant opportunities for the community than may have been initially conceived [2,16]. Even the simplest functional inclusions have this potential. For example, adding seating to a public space provides a simple rest stop in the first instance but invariably, where there are seats, there are social gatherings of community members. This simple amenity sets up this opportunity that can animate a previously quiet space, making it much more engaging and a safer environment for others to use. This has been demonstrated multiple times in urban people-place research spanning five decades [3,34,35].

The Hubs were designed to be social spaces, responding to the ideas that good public open spaces must be useful and meaningful to their users. The ChillOUT Hubs are seen to enhance the local area and make users feel included in the local community, whether they visited the space alone or with family or friends. Most respondents used a Hub to sit and rest, have lunch or coffee, wait for someone, or watch their children, making good use of the Hub as a social space. ChillOUT Hubs are very small social spaces with a footprint of approximately 10–15 m squared. As relatively small installations, they do not have the capacity to change the social dynamic of a large public space. However, they can create a small momentum of social activity around them, especially if they are co-located with other spaces like playgrounds or barbecue areas. They offer complimentary amenities which easily support and enhance social activity. Any comparable small-scale smart projects, like new tech-enabled, individual pieces of furniture (e.g., smart benches, bins or smart poles) do not share a similar social focus, for comparison.

Safety and well-being: As places continue to urbanize, cities need to combat the effects of the urban heat island and its effect on comfort and safety in public spaces [20]. Although the Hubs were designed to provide 'cool spots' in hot urban settings, those who did not use a Hub stated that there was not enough shade at the time they passed its location. This was especially evident on hot Australian summer afternoons. This substantiated the findings of specific heat studies, conducted in addition to this survey process by the same project team, that also found this design issue for all Hubs. Both users and non-users indicated that the design of the ChillOUT Hubs could be improved by providing additional microclimate mitigations (including controllable shade structures), water taps, plantings, and a mist machine for summer and a heater for winter for their personal comfort and safety. Hub users and non-users suggested the addition of 'seating with backs' (a preference of both seniors and parents with children). The use of armrests and back support aid the elderly provide support when getting up and down, and increase comfort, especially in areas where people sit for longer periods of time [19].

Personal safety became a priority when ChillOUT Hub users considered the intersection between street furniture and technology in public spaces. Users ranked security cameras and emergency buttons as desired features over other technologies (which were not safety-focused). Females and those aged over 65 years ranked an emergency button as a top priority. Security cameras were more of a priority for Hub users aged 25 to 39 years. Digital maps were a much higher priority for younger and male respondents.

Engagement with technology in public space: The new Hubs themselves and the specific amenities offered as part of street furniture are seen to improve the quality of their locations. Adding technology to the built environment is a contemporary addition with the potential to be a social enabler and digital includer. Not only does it add amenities that are appreciated, such as free power, charging facilities, water, and access to information, its inclusion often leads to new spatial opportunities that did not exist previously and which offer a new social node in the fabric of streets, parks, or plazas.

Inclusion in the digital world can now occur anywhere and facilitating users' technological engagement can be a recognition that they belong in public spaces. This was especially relevant for younger age groups and those who regularly work in the public domain. The use of the technologies was greatest among (older) students staying for long periods of time. Wi-Fi and charging points were heavily used at the Hubs.

The technology Hub at the center of this research was appreciated for its innovation and the opportunity brought by its technology. It was appreciated for just being there to uplift the physical environment and enable the community's desired social interaction in both the physical space and also the digital world. As argued by many experts, public places need to be comfortable and inviting [2,19,23]. In the contemporary world, they also should be digitally enabled for people to study, work, or play.

5. Conclusions

From both practice and theory, it is well-documented that the smart cities movement is making a significant impression on how cities are now designed, used and managed [1,6,32]. More specifically, the use of digital technologies, such as Apps, sensors, Internet of Things, and social media platforms, are going to continue influencing the use and performance of infrastructure in public spaces [10–12]. In addition to offering standard street furniture functions, designers are applying smart features to next generation, outdoor micro-infrastructures such as street poles, water fountains, benches, and tables. They are also inventing new pieces, like the ChillOUT Hub.

As evidenced by this research, basic technology such as Wi-Fi, charging points, smart lighting and more complex devices such as CCTV cameras, emergency buttons, and interactive maps are welcome in the public domain. Additional smart features that would improve personal comfort are also desired in the design of street furniture, such as cooling/misting features, heaters, and adjustable shading. However, Bishop and Marshall [14] stress the importance of using technology appropriately; if done well, it can foster positive people–place relationships in local neighborhoods. It has also been noted by Loukaitou-Sideris et al. [12] (p. 204) that adding technology "does not necessarily hinder interaction among people; it can facilitate conversations about the news of the day, encourage shared social activities. . ." further contributing to social connectivity.

Smart street furniture is evolving quickly. Smart poles, benches, garbage bins, and lighting are becoming commonplace in open spaces [12]. New products take time to prototype, test, redesign, and commercialize, and it takes time for the use of street furniture with electronics to be normalized by its users when in public open spaces.

This research concludes that there is significant social value in digitally enabled public open space and the role smart street furniture can play in creating social spaces, improving public safety, mitigating urban microclimates, and activating public spaces. It has also highlighted that there are always design improvements that can be made to street furniture to improve the experience of a place. This research was caried out by designers and providers of street furniture who are looking for a commercial edge when designing new, technology-enabled products, but who are also trying to improve the value of basic infrastructure and positively contribute to the evidence-based production of contemporary public space. Smart city technology is becoming readily available to continually provide an evidence-base for planners and city authorities—this should ultimately lead to better designed and better-managed public open spaces.

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Review

Design and Site-Related Factors Impacting the Cooling Performance of Urban Parks in Different Climate Zones: A Systematic Review

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Abstract: As cities expand rapidly, the combined effects of urbanization, global warming, and the intensification of the Urban Heat Island (UHI) phenomenon have become more challenging for urban environments. In response, Urban Green Infrastructure (UGI) has gained attention as a practical and effective tool for mitigating UHI and improving climate change. Among various UGIs, urban parks have been the subject of numerous studies due to their proven ability to reduce air and surface temperatures, improve local microclimates, and enhance overall urban livability. This systematic review synthesizes the existing body of research to identify key factors that influence the cooling performance of urban parks. A total of 131 peer-reviewed studies between 2014 and 2024 were analyzed, focusing on both design-related and site-related factors that play pivotal roles in a park's cooling effectiveness. Design-related factors include park size, shape, vegetation density and composition, the presence of water bodies, and impervious surfaces while site-related factors encompass background climate conditions, the proximity to natural water bodies, and the urban configuration surrounding the parks. The findings reveal that park size, tree coverage, and the presence of water bodies are the most influential design-related factors in enhancing cooling performance. For site-related factors, wind speed and direction emerged as critical components for maximizing cooling benefits. Research also showed urban configuration can affect the overall cooling performance by influencing airflow patterns and shading. Understanding these dynamics is crucial for cities worldwide as they strive to design parks that address their specific environmental and climatic challenges. The findings of this review offer practical guidance for landscape architects and urban planners, enabling them to design parks that deliver enhanced cooling benefits, especially when cities face rising temperatures and an increasing number of heatwaves.

Keywords: urban park; cooling impact; heatwave; Urban Green Infrastructure (UGI); Urban Heat Island (UHI)

1. Introduction

The world is undergoing rapid urbanization, with the global urban population growing from 30% in 1950 to 55% in 2018, with projections indicating a rise to 68% by 2050 [1]. To accommodate this growing population, metropolitan areas are increasingly being covered with buildings, replacing natural surfaces with impervious materials that retain heat and alter local energy dynamics, radiation, and atmospheric conditions [2]. These transformations create complex interactions between natural and urban environments, highlighting the need for context-specific design strategies that consider site and design-related factors to optimize both existing and future Urban Green Infrastructure (UGI) development.

One major consequence of these changes is the Urban Heat Island (UHI) effect, characterized by higher temperatures in cities compared to rural areas [3]. This phenomenon is exacerbated by climate change and extreme heat events, resulting in prolonged periods of high temperatures during summer. UHI significantly undermines urban sustainability

by worsening air quality, increasing energy and water consumption, impairing residents' well-being, raising heat-related mortality, disrupting ecological cycles, and elevating pollution levels [4,5]. Vulnerable communities, such as infants, older adults, pregnant women, individuals with chronic conditions, outdoor workers, and marginalized communities, are particularly more at risk from the adverse effects of UHIs [6,7].

UGI is identified as an effective and sustainable solution to mitigate the adverse impacts of UHIs [8–11]. UGI refers to a strategically planned network of natural and semi-natural areas within cities [12], primarily composed of vegetation and water [13]. It contributes significantly to microclimate regulation, where vegetation reduces surrounding temperatures through shading and evapotranspiration [14,15]. UGIs are cost-effective, environmentally friendly, and socially acceptable, making them a superior strategy for UHI mitigation [16,17]. UGI includes various elements such as urban parks, green roofs and walls, and street trees, each providing cooling benefits at different scales and helping cities combat climate change. However, designing climate-adaptive UGI requires careful consideration of the complex interplay between design-related factors and site-specific conditions.

Green roofs, for instance, reduce heat absorption and lower temperatures, although their effectiveness is influenced by factors such as vegetation type, growing medium depth, and local climate conditions [18–20]. Implementing green roofs requires careful planning and maintenance, and their initial cost can be a barrier to widespread adoption [21]. A study in Melbourne has shown that green roofs can reduce air temperatures by up to 1.5 °C and enhance thermal comfort by 2.38 °C on hot summer days [18]. Similarly, widespread adoption of vegetative rooftops in Chicago could lower temperatures by up to 3 °C [22]. However, research in Tokyo and Los Angeles has indicated that green roofs on taller buildings do not significantly improve street-level thermal comfort due to their height [23,24].

In contrast, green walls are generally considered more effective than green roofs in enhancing thermal comfort at pedestrian level in urban canyons [25]. Studies in Singapore and Perth have demonstrated that green walls can reduce surface and air temperatures by up to 4.36 °C and 4 °C, respectively [26,27]. In high-density cities, where the surface area of buildings often exceeds the available roof and ground space, green walls present an intriguing alternative for UHI mitigation. For instance, research in Melbourne's Central Business District (CBD) identified over 16 hectares of wall space with potential for greening [28]. Despite the challenges associated with green roofs and walls, they remain among the most effective solutions for mitigating UHI effects, especially in urban areas with limited open spaces.

Street trees also offer significant cooling benefits through shading and evapotranspiration. Their effectiveness, however, is influenced by the surrounding urban environment, including street geometry, building heights, and surface materials [29,30]. The cooling benefits of street trees are highly localized, with research indicating that their effectiveness increases as street canyons become shallower and broader [29].

Among all UGIs, this review focuses on urban parks due to their capacity to address critical urban challenges, particularly the mitigation of UHIs [31–34]. Urban parks, characterized by their dense vegetation, play a crucial role in cooling urban environments through mechanisms such as evapotranspiration and shading [14]. This cooling effect, known as the Park Cool Intensity (PCI), refers to the temperature difference between the cooler park area and its warmer surroundings [35–38]. The cooling benefits of urban parks can be extended beyond the park's boundaries, influencing nearby urban areas through air convection and heat exchange processes [39,40]. Despite extensive research on the benefits of urban parks, no comprehensive study has systematically compiled the factors influencing their cooling performance.

To address such research gap, this review synthesizes existing knowledge by classifying the factors influencing park cooling performance into two categories. First, design-related factors known as the factors directly determined by landscape designers, are

discussed. Following this, site-related factors, which are external influences impacting the internal cooling performance of parks, are examined. This structured approach helps clarify the different dimensions shaping the cooling capacity of urban parks. Additionally, it explores how the PCI and Park Cooling Distance (PCD) vary across different climate zones.

To measure the cooling impact of parks, a number of metrics is used in the literature. Land Surface Temperature (LST), Park Cooling Area (PCA), Park Cooling Efficiency (PCE), and PCD are often used in studies to evaluate the cooling performance of urban parks. PCA refers to the maximum buffer area (Smax) influenced by a park's cooling effect, representing the largest area over which a park can significantly reduce temperatures, including a buffer zone of width D measured from the park's edge. PCE, on the other hand, reflects the ratio of PCA to the park's area (PCE = PCA/Spark), where Spark denotes the size of the park, and represents the cooling effect per unit area [31,41]. PCD is defined as the horizontal cooling distance in meters from the park boundary to the first turning point in the temperature–distance relationship, indicating how far the cooling effect extends beyond the park [42,43]. Finally, PCI, often retrieved from satellite images, is calculated as the ratio of LST reduction due to the park to the original LST within a given cooling distance, representing the cooling sensation experienced by local residents. A higher PCI value indicates a stronger cooling impact [41].

While it is well-established that parks can cool the air, their cooling performance varies across studies due to differences in design factors and site-specific conditions. This systematic review provides a comprehensive overview of both design and site-related factors affecting urban park cooling. Additionally, it explores how background climate conditions impact PCI intensity. The insights gained from this review are intended to assist landscape architects, designers, and urban planners in maximizing the cooling potential of parks through informed design choices and strategic planning.

2. Materials and Methods

This systematic literature review aims to synthesize existing research on the design and site-related variables that influence the cooling performance of urban parks. Comprehensive searches were conducted in several academic databases, including "Scopus" and "Web of Science", using the keywords: *Park* AND ("*Cool* Island*" *OR* "*Cool* Effect*" *OR* "*Cool* Impact*" *OR* "*Cool* Performance*" *OR* "*Cool* Intensit**"). The search was carried out on 12 July 2024, and was restricted to peer-reviewed articles published in English between 2014 and 2024. Conference papers, reports, and book chapters were excluded from the results.

The search yielded 188 papers. The review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure a rigorous and unbiased analysis of relevant studies [44]. Each study was meticulously screened to assess its relevance, focusing on the clarity of objectives, robustness of methods, and relevance of outcomes. Studies lacking clear objectives, employing weak methodologies, or presenting findings unrelated to the scope of this review were excluded. The review primarily concentrated on studies addressing the PCI effect, as well as design and site-related factors influencing PCI. Papers that focused solely on LST without addressing PCI were excluded. After applying these criteria, 131 studies were selected for detailed analysis, as illustrated in Figure 1.

Five main sorts of information were extracted from the selected articles: location, climatic zones, objective of study, methods, and cooling performance results. The selected studies were categorized into three main sections for analysis. The first section examines design-related variables that impact the cooling performance of urban parks, such as park size and shape, vegetation characteristics, and the presence of water features. The second section focuses on site-related variables, including the local climate conditions, distance from natural water bodies, and the characteristics of the surrounding built environment that influence the parks' cooling effect. The final section discusses the variation in the park's cooling impact in different climates and identifies gaps in the current literature.

This structured approach provides a comprehensive understanding of how both park design factors and site-related variables influence the cooling performance of urban parks. The insights gained from this review are intended to inform future research and practical applications in urban heat mitigation.

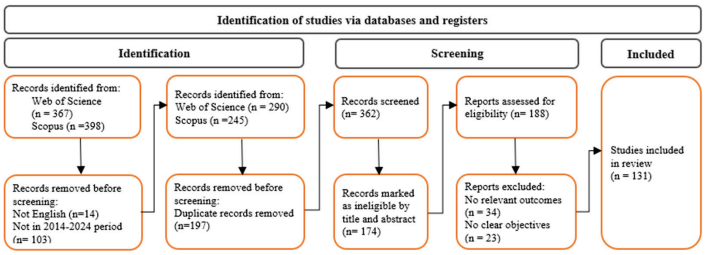


Figure 1. PRISMA flowchart of the selection of studies.

3. Urban Parks

While a substantial body of literature has explored the factors affecting PCI, the findings are scattered and often lack a coherent organizational structure. This fragmentation highlights the need for a systematic classification of these factors to provide clearer insights into park cooling mechanisms. To address this gap, the next section categorizes the factors influencing PCI into two primary groups: design-related parameters, which landscape designers and policymakers directly control, and site-related parameters, which are external influences affecting a park's cooling performance. This approach will help streamline the extensive research on PCI and offer a more structured understanding of the key determinants of urban park cooling.

Urban parks play a crucial role in mitigating the UHI effect through a phenomenon known as the PCI effect, which provides significant cooling benefits that enhance thermal comfort in densely built environments [45]. The PCI effect occurs when urban parks maintain lower temperatures than their surrounding areas, largely due to natural features such as vegetation, water bodies, and other landscape elements that provide shading and facilitate evapotranspiration. Several factors influence the PCI effect, including park size, shape, vegetation density, and the surrounding urban infrastructure [46,47]. These factors, along with the specific climatic and urban context, significantly impact the cooling effectiveness of parks.

3.1. Design-Related Factors

3.1.1. Park Size

One of the key parameters impacting the cooling effect of urban parks is their size. Many studies have consistently shown that the cooling effect of urban parks on their surroundings is directly proportional to their size [31,41,43,48–55]. Research indicates that park size alone can explain up to 30% of temperature variability within urban parks [56]. For example, a study in Melbourne reported an average PCI of 3.28 °C in large parks, compared to 2.25 °C in medium parks and 1.69 °C in small parks, indicating a strong correlation between size and cooling performance [33]. Similarly, in Changsha, China, doubling the park size was shown to increase the PCI by 0.8 K [48].

Further supporting this relationship, a study in Jinan, China, found that only parks larger than a threshold size of 20 hectares provided a substantial increase in cooling effect with size [57]. Likewise, in Nigeria, parks larger than 28.67 hectares ensured a stronger PCI, while those smaller than 8.28 hectares exhibited a lower PCI [58]. In Hong Kong, reducing UHI intensity was found to be closely related to park size [32]. This finding is consistent with studies from Melbourne and Wuhan, China, where large parks significantly decreased temperatures in surrounding built-up areas, whereas medium and small parks demonstrated lower efficiency in mitigating UHI [33,59]. One reason for this impact is the "park breeze" effect, a phenomenon in which temperature differences create airflow that enhances air circulation in and around the park [60].

A study in Moscow found that large parks exhibited better cooling effectiveness due to a stronger park breeze effect, which enhances air divergence over green spaces. The park breeze is almost negligible in small and medium-sized parks [49]. This feature can significantly reduce urban heat stress as wind speed increases [61]. A study in Tokyo recorded park breezes, or cold airflows, extending into urban areas for 21 nights over two summer months. These breezes often reached depths of at least 16 m and traveled more than 122 m from the park edge [62]. In Melbourne, research showed that large parks extended their cooling effects as far as 2000–2500 m [33], while a study in Poland found park cooling distance to be between 100 and 925 m for parks ranging from 8.4 to 76.87 hectares [63].

Large parks also support a greater density and variety of vegetation, which enhances cooling through evapotranspiration and helps reduce UHI effects [32,64,65]. In Beijing, research found a non-linear relationship between park size and transpiration rate, indicating that maximum transpiration might occur at a specific park size. This finding underscores the importance of selecting appropriate tree species to maximize cooling performance [66].

Studies on the impact of a park's size on cooling effects also showed that while large parks generally exhibit higher and broader PCI, smaller parks often provide better cooling intensity per unit area [40,59,67,68]. For urban populations, small and medium parks located within walking distance are more valuable for everyday climate comfort than larger, less accessible parks [49,69]. In areas with high UHI intensity, such as urban industrial and commercial zones, small comprehensive parks are recommended for more efficient UHI mitigation, significantly impacting citizens' health and well-being [59,70].

Research on 41 pocket parks in Shanghai, ranging from 0.17 to 3.5 hectares, revealed that 90% of these parks were cooler than their surroundings, with only those smaller than one hectare being hotter [71]. Similarly, a study of 41 parks in Changzhou found that parks smaller than 1.34 hectares had minimal impact on the surrounding air temperature [72]. To optimize cooling benefits for parks less than one hectare, maximizing vegetation coverage is recommended [73].

The challenges for small urban parks arise from their susceptibility to surrounding built-up areas and roads, which can diminish their cooling impact [74]. Research in Hong Kong further suggested that urban parks should be large enough to buffer against the negative impacts of surrounding built-up areas on PCI, ensuring a stable cooling and humidifying effect [75]. For high-density areas, site selection becomes crucial, with priority given to locations away from busy roads to enhance the cooling potential [76].

While larger parks generally yield stronger and broader cooling effect [40,46,49,50, 57,59,74,77–79], the relationship between park size and cooling intensity is not linear but follows a logarithmic pattern [31,41,48,51,53]. The cooling efficiency of urban parks increases at a decreasing rate until the park size reaches a threshold known as the Threshold Value of Efficiency (TVoE) [31,35,41,74], beyond this point, further increases in park size yield diminishing returns in cooling effects [51,57,65,77,79–82].

This phenomenon occurs because larger parks develop their internal microclimate, where air temperatures stabilize, and additional increases in size do not significantly lower temperatures further [78,83]. The TVoE for urban parks is highly influenced by the local background climate [51,84]. For example, a study examining PCI across 29 cities in China revealed that the TVoE varies from 16 to 19 hectares in humid, arid, and semi-arid areas [81]. Similarly, a study on PCI in seven different Chinese cities found that cities with higher average background temperatures tend to require larger optimal park sizes [85]. This study also found that parks located in hotter urban areas demonstrate enhanced cooling effects, with PCI differences exceeding 0.4 °C, and larger TVoE observed in these regions.

The TVoE is also heavily influenced by rich and healthy vegetation coverage. In Southeast Asia, the optimal park size for cooling varies depending on background temperature and vegetation cover, with larger parks required in areas with high background temperatures and rich vegetation [35]. Research also showed that the TVoE for park size decreases from high to low latitudes, meaning that smaller parks in low-latitude areas

can achieve similar cooling effects as larger parks in high-latitude areas. This suggests that urban parks in low-latitude regions tend to exhibit greater cooling effects than those in higher-latitude regions [79]. Table A1 provides a summary of studies focusing on the impact of park size on PCI.

3.1.2. Park Shape

Park shape is another significant factor affecting PCI [52–54,63,71,72,78,86–90]. The significance of park shape becomes especially apparent in parks larger than one hectare in open built-up zones, where shape complexity can influence cooling effectiveness [73]. In Nanjing, China, researchers found that round and square-shaped parks had the greatest cooling effects, followed by round parks with a strip tendency, and then strip parks [82,91]. This finding aligns with research from Nigeria, where near-circular green spaces produced stronger PCI effects [58]. Researchers also found the lowest PCI for street and linear parks [46]. Regularly shaped parks also tend to produce a greater cooling extension compared to irregularly shaped ones [82].

However, the relationship between park shape and cooling efficiency is not always consistent, with contradictory findings reported across different cases. Some studies suggest that parks with complex shapes can enhance their cooling impact by interacting more extensively with the surrounding urban environment, thereby increasing the PCI [31,48,49]. For instance, a study in six cities in China found that intricately shaped parks expanded their radiative services, benefiting more distant residential zones [41]. Similarly, in Xi'an, China, large, dense, and complex-shaped parks demonstrated strong interactions with their surroundings, further enhancing their cooling effects [40].

By contrast, some research indicates that increased shape complexity may reduce cooling intensity, suggesting a negative correlation with PCI [46,53,58,90,92]. This phenomenon may be attributed to increased thermal exchange at complex boundaries, which often interact with other land cover types like impervious surfaces and residential areas, resulting in higher temperatures compared to more compact green spaces [77]. Furthermore, higher shape complexity can fragment greenspace and decrease connectivity, thereby diminishing cooling effects [93]. A study in Addis Ababa observed that parks with higher shape indices had greater cooling extension but lower cooling intensity. This suggests that while compact, circular parks exhibit stronger thermal contrast with their immediate surroundings, irregularly shaped parks extend their cooling influence over a larger area [90].

Contradictions also exist in the relationship between park shape and surface temperature. A study reported that increasing the complexity of green space shapes could efficiently decrease LST [94]. Similarly, studies in Jinan and Changzhou, China, found a negative correlation between park shape index and LST, although some parks with complex shapes showed no significant correlation with LST due to surrounding water bodies, which lowered their overall temperatures [57,72]. However, a study in Delhi found that more complex park shapes failed to provide a cooling impact and even increased LST [95].

Similarly to the influence of urban park size, specific thresholds also exist for the impact of shape complexity on cooling performance. For example, in Copenhagen, Denmark, it was found that when blue–green parks exceed one hectare, complex shapes still maintain a strong cooling effect [2]. In Nanjing, China, it was observed that in parks ranging from one to twenty hectares, complex shapes produced cooling effects between 2.6 and 3.6 °C, while regular shapes provided cooling between 2.4 and 4.7 °C, showing that reducing shape complexity in parks larger than five hectares enhanced cooling intensity [82]. In Leipzig, Germany, a study of 62 urban parks found that shape complexity positively affects park cooling distance for greenspaces smaller than 6.27 hectares but negatively affects those larger than this threshold [96]. The review of the studies showed that the connection between park shape and PCI is complex and context-dependent. A study of 207 urban parks across 27 cities in China found that in high-latitude and dry areas, simpler shapes with less landscape fragmentation benefit the cooling effect of urban parks [79]. Table A2 provides a summary of studies focusing on the impact of shape on PCI.

3.1.3. Urban Park's Vegetation Characteristics

Vegetation characteristics, which refer to the specific features or attributes of plant life that influence their behavior and ecological function, could also impact the cooling effects provided by urban parks. Specifically in trees, factors such as tree height, canopy attributes—including Leaf Area Index (LAI) and Sky View Factor (SVF)—and the characteristics of deciduous versus evergreen species all contribute significantly to PCI, particularly during heat events when cooling is most needed [34,52,60,84,86,94,97–103]. Studies have also shown a negative correlation between vegetation coverage and LST [2,46,72,73].

Vegetation metrics, particularly during extreme heat and normal days, contribute 47.1% to the park's cooling performance [99]. However, studies show that while the cooling effect of trees is most significant in the evening, high summer temperatures can diminish this effect by limiting vegetation transpiration [51,104]. In Beijing, research demonstrated that as local temperatures rise, the cooling effect follows a hump-shaped curve, flattening or decreasing once a certain temperature threshold is reached [97]. Similarly, a study in Leipzig, Germany, found that during dry and hot conditions, the cooling effect beyond park boundaries was less than 1 °C [105].

Tree Canopy Structure: Among various types of vegetation, trees play a particularly significant role in mitigating UHIs through both shading and evapotranspiration [60]. These processes can reduce heat stress and create more comfortable environments [106]. A study in Beijing's Olympic Park revealed that trees contribute more to air temperature reduction than grasses and water bodies, primarily due to the shade they provide [107]. However, the effects of evapotranspiration and shading are seasonally dependent. Transpiration rates peak in summer and decrease in winter, while shading efficiency varies with seasonal changes in leaf cover—deciduous trees provide less shade in winter, whereas evergreen species offer consistent year-round shading [108]. Factors such as LAI, canopy size and density, and crown height are also critical in determining the cooling benefits of trees.

The structure of a tree's canopy plays a pivotal role in its cooling effects through shading, with studies showing that greater canopy coverage enhances park cooling intensity [97,108–110]. The ratio of crown diameter to branching position height (D/PH) also has a notable microclimatic impact, with higher D/PH values enhancing photosynthesis, respiration, and shading, thus improving cooling intensity during hot weather [111]. Similarly, research on 16 tree species in Gold Coast, Australia, revealed that trees with wider crowns and higher leaf quantities create optimal thermal environments during summer [112]. High canopy density is particularly beneficial as it ensures maximum shading and minimizes the mean radiant temperature under the tree crown [112]. In addition, an increase in leaf quantity enhances the transpiration rate, a vital cooling mechanism in trees, thereby improving their overall cooling capacity [97].

Canopy density and the distribution of canopy layers further influence cooling effects. Research indicates that dense, unevenly distributed canopies at higher layers provide superior cooling during summer [72,109,113]. In urban residential parks, where visitors tend to be outdoors during the hottest parts of the day, selecting tree species with broad, dense canopies can significantly improve thermal comfort [114], and provide more effective microclimatic regulation through shading [111]. Research conducted in Puebla, Mexico, showed that trees like Indian laurel, which have dense canopy layers and oblate shapes, provide more shade and cooling compared to other trees like Eucalyptus, as well as grass cover and other vegetation [56].

However, dense tree canopies, especially in broad-leaved communities, can obstruct airflow, limiting heat exchange with the surrounding environment [115]. In such cases, the height of the tree crown becomes a critical factor, as it not only influences airflow but also helps mitigate the effects of increased solar radiation [116]. For instance, a study in Wuhan demonstrated that taller trees with canopy shading created a stronger cooling effect, with a maximum temperature reduction of 2.8 °C [117]. Strategically planting trees with larger canopy areas can significantly enhance park cooling intensity, while taller trees improve air circulation, further contributing to cooling [67,97]. Research in Suwon, Republic of

Korea, observed that tall, dense-crowned trees created "warm" Physiological Equivalent Temperature (PET) conditions, two levels cooler than in sunny locations [118].

The effectiveness of tree canopies in intercepting solar radiation fluctuates throughout the day as the angle and intensity of sunlight change. A study found that in regions with high solar radiation, such as Alice Springs and Lahore, shading plays a crucial role in reducing thermal sensation within parks. However, in areas with fewer hours of full sun and more cloudy conditions, such as Kuala Lumpur, shading is somewhat less effective [119]. When sunlight is at a lower angle and radiation intensity is weaker, cooling is primarily influenced by canopy density. However, as the sun's angle rises and radiation becomes stronger, both canopy density and the LAI play a critical role in enhancing cooling effects [66,118,120]. Additionally, canopy density and overall coverage are significant contributors to the humidifying effects within plant communities. More complex canopy structures, particularly those with understory shrubs, further enhance humidity levels, amplifying the cooling benefits [113]. LAI and SVF are two important metrics frequently used in studies to assess the impact of tree canopy on cooling performance and microclimatic regulation.

Leaf Area Index (LAI): LAI—one-sided green leaf area per unit ground surface area (LAI = leaf area/ground area, m^2/m^2)—is another crucial factor positively correlated with PCI [72,88,92,113], Studies in Gold Coast and Xindu, China, demonstrate that increasing LAI by one point can raise PCI by 0.31 °C and reduce air temperature by 2.5 °C, respectively [121,122]. However, a study in Chongqing, China, found that the impact of LAI differs near water bodies. Specifically, tree species with low LAI had a greater cooling effect on the surrounding waterfront thermal environment. When LAI decreased by 1.0, the average cooling effect increased by 0.19–0.31 °C [123].

Sky View Factor (SVF): SVF beneath the trees also correlates with PCI. Lower SVF values correlating with better shade levels, PCI, and Mean Radiant Temperature (MRT) [124]. Findings revealed that increasing the SVF value by 0.1 can cause an air temperature rise of around 1 °C, an air velocity increase of 0.16 m/s, a solar radiation increase of 40 W/m^2, and a mean radiant temperature rise of nearly 1.6 °C [122]. However, studies indicate that LAI has a more significant cooling effect than SVF [122]. Further research showed a significant correlation between SVF and average crown diameter, demonstrating that SVF decreases as the average crown diameter of trees increases. When the average crown diameter is less than 1.5 m, SVF increases dramatically, and shaded areas substantially decrease [125].

Tree Species: The cooling effectiveness of trees also varies depending on their species. Deciduous trees, for example, are more effective in regulating microclimates than evergreens due to their seasonal leaf shedding, which allows more sunlight to penetrate in winter and provides more shade in summer [126,127]. In China's humid continental climate, coniferous trees provided the highest cooling and humidification effects, achieving 3.38 °C reductions, compared to broad-leaved communities, which cool by 3.24 °C [115]. Similarly, on Haitan Island, China, evergreen coniferous clusters provided the greatest cooling effect at 1.40 °C, followed by deciduous broadleaf clusters at 1.31 °C, and evergreen broadleaf clusters at 1.30 °C. Palm clusters exhibited the lowest cooling impact, at only 0.93 °C [110].

Trees vs. Turfgrass: Several studies highlight the distinct cooling effects of trees versus turfgrass in urban parks. Tree-dominated parks generally show higher PCI than those primarily covered by turfgrass [72,92]. For instance, in San Francisco, dense tree areas achieved cooling intensities between 1.9 °C and 3.7 °C, while grass-covered areas ranged from 0.9 °C to 2.6 °C, depending on meteorological conditions [37]. Given turfgrass's limited cooling potential, several studies recommend replacing it with trees or shrubs to improve the cooling benefits of urban parks [76].

However, well-irrigated grass-covered parks can also provide notable cooling, especially in specific climates. A study found that while tree-covered parks are especially effective in mitigating the UHI effect in Temperate Monsoon Climates and Mediterranean Climate zones, grass-covered parks also contribute to cooling in Mediterranean environments when

adequately irrigated [128]. Another study in UT, USA, revealed that turfgrass offers significant cooling potential at night. This is due to turfgrass's evapotranspiration, which is amplified by high atmospheric evaporative demand, soil moisture availability, and increased radiation loads typical of semi-arid urban landscapes [129]. This highlights the context-dependent nature of vegetation choices in enhancing urban park cooling performance.

Research has also demonstrated the benefits of combining different types of vegetation. A study showed that parks with mixed vegetation such as trees planted near water bodies or grass areas interspersed with trees, outperformed areas dominated by a single vegetation type in enhancing microclimate stability [130]. Findings from Shanghai also revealed that parks with a mix of trees and shrubs exhibited the lowest surface temperatures, while those with a single type of vegetation showed higher LST, further supporting the idea that diverse vegetation is more effective in reducing LST [71]. These results align with findings from studies conducted in Delhi, India, and Taipei, Taiwan, where diverse vegetation types were more effective in providing cooling benefits than monoculture approaches [60,95]. Table A3 summarizes the locations, climate conditions, and key details of studies that primarily focus on the role of vegetation in influencing PCI.

3.1.4. Vegetation Coverage and Spatial Arrangement

In urban environments where creating large park patches is often challenging, optimizing the landscape composition and configuration within existing parks becomes essential for enhancing their cooling performance. Many studies underscore the critical role of strategic vegetation management in improving the cooling effects of urban parks [32,42,46,48,53,54,60,70,88,90,92,96,131–133] and reducing the magnitude of the surface temperature [95,103,134]. For instance, higher vegetation coverage has been shown to significantly lower temperatures, as it increases above-ground biomass, which blocks sunlight, enhances evapotranspiration, and absorbs heat, thus creating a stronger cool island effect [56,72]. This is consistent with findings from Beijing, where larger parks with higher vegetation coverage demonstrate superior cooling efficiency [64]. Studies in Delhi and Beijing also revealed that dense vegetation and trees always have a negative correlation with the LST [95,103].

Multiple studies indicate that increasing vegetation coverage significantly enhances cooling. For example, in Hong Kong, a 10% increase in shrub and tree cover was associated with mean temperature reductions of 0.07 °C and 0.04 °C, respectively [75]. This is consistent with findings in Beijing, a 10% increase in green space ratio correlates with a 0.16 °C temperature reduction [135]. Similarly, in Nanjing, China research highlights that an increase of 10% in forest-vegetation area can lead to a temperature reduction of approximately 0.83 °C [89,131]. A study found that 70% of the influence that the urban forest provides on the immediate surroundings can be explained by the number of trees [136]. Research in Poland demonstrated that larger parks, particularly those with forested areas, have better cooling efficiency than smaller ones [63]. Studies recommend vegetation coverage of around 40% to maximize PCI in urban areas like Zhejiang and Hong Kong [32,133].

The spatial arrangement of vegetation within parks also significantly affects cooling efficacy. Research indicates that group planting enhances cooling benefits more effectively than linear or isolated planting [126]. For instance, in Xi'an, China, research indicated that densely vegetated green spaces are more effective in spreading cooling effects than fragmented green spaces, which may have their cooling effects neutralized by internal factors before they can benefit surrounding areas [132]. Similar findings in Suwon, Republic of Korea, suggest that creating shaded areas in groups rather than at intervals is more effective for cooling [118]. However, it is important to note that significantly increasing landscape coverage can negatively impact winter outdoor thermal comfort [137]. Furthermore, dense vegetation arrangements can reduce wind flow, creating poorly ventilated hotspots that may undermine cooling effects [118,126,138].

Given that increased wind speed can significantly lower temperatures around tree-covered areas [46,69,81,92,128], it is recommended to optimize planting coverage with

sufficient spacing between tree crowns and creating ventilated corridors aligned with prevailing winds to enhance cooling [118,139], specifically in warm-humid climates [136,140]. In Colombo, Sri Lanka, densified planting arrangements were found to worsen wind speed, MRT, and PET, though not for air temperature. Thus, MRT and wind speed are crucial factors for thermal discomfort in warm-humid outdoors compared to air temperature [140].

The wind speed tends to enhance cooling intensity in downwind areas by enhancing evapotranspiration while weakening it upwind [34,115,141,142]. For example, in Shanghai, tree corridors aligned with prevailing wind directions showed better cooling effects [143]. In Tabriz, Iran, the direction of tree rows in different planting patterns had varying effects on air temperature reduction. In a triangular planting pattern with a direction parallel to the wind, air temperature decreased, while in a rectangular planting pattern with rows of trees perpendicular to the wind direction, it increased [127]. Similarly, a study in Berlin found that combining trees with large canopies and belt-shaped green areas parallel to the wind direction could achieve significant microclimate and thermal improvements [88].

Another study focusing on rectangular and triangular planting found that a rectangular planting pattern, with evergreen trees on the outer rows and deciduous trees on the inner rows, oriented parallel to prevailing winds, has been found to produce the most optimal cooling conditions [127]. A study in Melbourne found that a downwind propagation of the cooling effect of the park can be extended up to one-half a park width away from the park [106]. Similarly, a study in Tokyo found that the park's thermal influence extended farther on the downwind side (450 m) than on the upwind side (65 m). Even on calm nights, the thermal influence extended by the park breeze averaged 200 m from the park boundary [142].

In addition to vegetation layout, planning must consider factors like the number of sunny days per year and the sun's position during hot seasons to maximize shaded areas [118]. A comparative study across five cities with different climates suggests that in very hot and sunny zones, maximizing year-round shade is essential. For example, parks in Lahore should be designed to resemble forests to provide maximum cooling. In contrast, cities with cold seasons that benefit from solar radiation and reduced wind speeds, such as Toronto, should incorporate a mix of coniferous and deciduous trees along with open landscaped areas. In climates with partly cloudy conditions, a combination of open spaces and groves is recommended to accommodate varying radiation scenarios [119]. Table A4 summarizes studies focused on tree planting patterns and vegetation coverage. It is important to note that while some studies detailed the cooling behavior of parks, they did not provide numerical values for the PCI. As a result, the specific PCI values for those studies cannot be included in the table.

3.1.5. Water Features

Water features, including ponds, lakes, and fountains, are common elements in urban parks that contribute significantly to the cooling effects of urban parks, lowering surrounding temperatures and enhancing thermal comfort [2,57,70,72,74,103,134]. Various studies have consistently found that the size of internal water bodies in urban parks significantly correlates with their cooling intensity and efficiency [38–41,46,47,53,54,56,65,68,72,94]. For instance, research conducted across diverse climate zones in China found that parks with water bodies achieve better cooling efficiency than those without, even in smaller parks [78]. Similarly, a study in Hong Kong revealed that simple water features, like fountains or sprinklers, can reduce ambient temperatures by up to 6.8 °C [61]. The cooling effects of water bodies can extend beyond their immediate surroundings, reaching up to 20 m beyond the borders of the blue space [123]. The TVoE is lower when parks contain water bodies, suggesting that incorporating or enlarging water features during landscape design can significantly boost cooling performance and mitigate the UHI effect [65,78,100].

The size and shape of water bodies also play crucial roles in their cooling performance. Faceted water bodies, for instance, exhibit stronger cooling intensity compared to linear ones [34,107]. In Shanghai, parks that effectively mitigate local thermal discomfort often

feature a higher percentage of water bodies, emphasizing the importance of incorporating these features into park designs [67]. Research further supports this by showing that a 10% increase in water cover within a park can enhance its PCI by 0.41 K [48]. Moreover, increasing the area of water bodies in parks has been linked to an increase in the cooling distance, with a study in Shanghai revealing that for every 10-hectare increase in park water bodies, the cooling distance extended by approximately 200 m [68].

This is further illustrated by a study in Copenhagen, Denmark, where water bodies were found to have a greater cooling extent and intensity than green spaces, including grass-covered areas [2]. Their study revealed that, in summer, the cooling extent and intensity of water bodies, greenspace, tree-covered and grass-covered green space were 180 m, 5.26 °C; 150 m, 2.65 °C; 145 m, 3.58 °C and 105 m, 2.21 °C respectively. In densely developed urban areas, regularly shaped parks with water bodies such as ponds and rain gardens can facilitate more pronounced temperature reductions, thereby enhancing the cooling experience for visitors [41]. A simulation-based study in Beijing, China, found that water bodies contributed to a maximum cooling effect of 1.3 °C in air temperature reduction, with more than 0.8 °C attributed to the water itself [144].

In densely developed areas, regularly shaped parks with water features can create more pronounced temperature reductions, while in residential neighborhoods, constructing parks with water features near existing lakes or low-lying areas can rapidly alleviate the UHI effect and enhance local thermal comfort [59]. Nonetheless, some studies have reported limited cooling impacts of water features. For example, research in Suzhou, China, found minimal cooling benefits from water bodies, possibly due to their small size relative to the park area and the influence of local wind conditions [92]. Similarly, another study in Beijing found that water bodies alone have limited capacity to mitigate heat in parks [130].

The cooling effects of water bodies are also subject to seasonal and diurnal variations. While they provide substantial cooling during the day, water bodies can contribute to a warmer and more humid microclimate at night, potentially reducing nighttime comfort for park visitors [64]. In a study conducted in Iloilo, Philippines, water bodies were associated with a nighttime temperature increase of up to 0.16 °C [141]. Additionally, simulations in Xi'an, China, revealed that while water features enhance cooling during summer, they can negatively impact thermal comfort in winter, particularly when water cover exceeds 15% of the park area [137]. Research in Zhejiang, China, further identified an optimal water coverage of 5% for balancing cooling benefits throughout the year [133]. Table A5 summarizes the findings of studies investigating the impact of internal water bodies on park cooling performance.

3.1.6. Water Vegetation Availability

Increasing irrigation is a key factor in enhancing the cooling intensity of urban parks [106]. Research indicates that the diurnal cooling effect of parks is significantly influenced by soil moisture content [106,129]. In semi-arid urban landscapes, higher soil moisture availability enhances turfgrass evapotranspiration, contributing to improved cooling [129]. The importance of irrigation, particularly for turfgrass, has been emphasized in several studies [145]. For instance, a study comparing the cooling performance of parks across five cities in the world found that landscapes dominated by turfgrass require higher irrigation than those comprising desert-adapted trees and shrubs due to the high evaporation rates associated with turf areas [119]. Proper irrigation regimes can significantly enhance the cooling effect of grasses. Irrigated grass can achieve a cooling effect similar to that of small water bodies on sunny, windless summer days [107].

On the other hand, drought-related water use reductions may limit or even discontinue the irrigation of public lawns, reducing their potential to maintain cooler temperatures and making their phenology similar to that of wild senescing grasslands [145]. In UT, USA, a study found that parks with intensively irrigated sports fields exhibited air temperatures similar to those of parks with higher tree canopy cover, underscoring the role of evapo-

transpiration and higher albedo in regulating the daytime energy balance in semi-arid landscapes [129].

Research focused on urban parks in Mediterranean and temperate monsoon climates found that increasing artificial rainfall and irrigation significantly improves the cooling intensity of grasslands, especially in hot-dry environments. This suggests that incorporating fountains into existing grasslands could substantially mitigate the UHI effect in Mediterranean cities [128]. Moreover, newly planted drought-resilient trees require intensive watering to establish their roots. However, once established, these trees become drought-tolerant and need far less water than grass, flowers, and other ornamental shrubs [56].

The texture of the soil also plays a significant role in the water needs of vegetation. For instance, a study in Hamburg found that plants growing on clayey soils suffer more from water stress during warm and dry periods, leading to reduced transpiration and a lower cooling effect. This finding is contrary to expectations, as clay-rich soils generally have a higher water storage capacity and are often found in floodplains with likely capillary contact with groundwater. However, the low unsaturated hydraulic conductivity in the fine pores of these soils limits the rate of root water uptake and capillary rise, thereby diminishing their cooling potential [146]. Although no studies specifically focused on the role of irrigation in influencing PCI, several have acknowledged it as a contributing factor. Table A6 provides a summary of the studies highlighting the impact of irrigation on PCI.

3.1.7. Impervious Surfaces

Impervious surfaces refer to artificial structures such as pavements typically covered with materials like asphalt, concrete, brick, and stone that impede water infiltration. The percentage of these surfaces in urban parks can impact the PCI. Parks with lower coverage of impervious surfaces tend to provide better PCI [42]. Impervious surfaces absorb more solar radiation, leading to higher surface temperature, which negatively impacts the cooling effect of urban parks [38,46,48,72,74,85,94]. Large parks with significant portions of impervious surfaces or bare land might be less effective at reducing temperatures than green spaces with more vegetated areas [56]. In smaller parks, where green areas are limited and paved areas are more prominent, pavements can absorb and reflect solar radiation, leading to temperature increases and the formation of heat islands, ultimately causing a thermal insulation phenomenon [92]. To mitigate these effects, impermeable pavement should be minimized in favor of more vegetation cover, which can improve soil and plant growth conditions [76].

The choice of surface materials also plays a significant role in the cooling performance of an urban park. For instance, a study found that cement bricks, grass flagstones, and coconut mats create better human thermal environments than baked bricks, polyurethane, and granite [118]. The combination of high-albedo pavements with wide-crown trees is considered one of the most effective strategies to enhance thermal comfort [116]. Moreover, replacing artificial land cover with natural elements such as grass, forests, and water can further boost cooling effects. For example, converting asphalt and concrete land covers to forested areas would create significant cool spots and provide substantial thermal benefits [147]. Although grass is not inherently endothermic, it reduces heat radiation absorption, leading to lower lawn temperatures compared to paved surfaces during the midday summer heat [92]. Table A7 summarizes the findings of studies focused on the impact of surface materials on PCI.

3.2. Site Related Factors

3.2.1. Background Climate

The location of a park and its background climate conditions are pivotal in shaping its cooling performance and influencing the effectiveness of design-related factors. Background climate refers to the long-term climatic characteristics of an area, which impact the local weather patterns and environmental dynamics. These conditions include key

meteorological elements such as temperature, humidity, precipitation, wind patterns, and solar radiation, all of which interact over extended periods to affect the park's cooling potential. A Study showed that the cooling intensity of parks tends to be weaker in cities with humid and hot summers compared to those with dry and hot summers [47]. While relative humidity in cities can limit the cooling effects of urban parks, increasing wind speed can significantly enhance the cooling impact of tree-covered areas [103]. Excessive humidity often reduces transpiration intensity in green spaces, thereby diminishing their cooling effects [128,132]. In Hong Kong, stronger cooling effects were observed on hotter days, while the humidifying effects were more pronounced on less humid days [75]. Another study in Hong Kong revealed that cloudy and windy conditions can weaken the cooling effects of landscapes, whereas strong solar radiation can enhance them [76].

Studies on cooling variation between parks have found that cooling performance can vary significantly with latitude. Latitude, a geographic coordinate specifying a location's north–south position on Earth's surface, influences climate, which in turn affects vegetation types, growing seasons, and ecological zones. Research has shown that the cooling performance of parks with water bodies differs notably across various climate regions. In arid and semi-arid areas, water bodies are the primary factor influencing PCI, whereas in semi-humid and humid regions, the surrounding climate has a greater impact, with water bodies being the second most influential factor. The optimal ratio of water bodies to vegetation in parks is approximately 1:2 in arid/semi-arid regions and 1:1 in semi-humid regions [81]. Another study focusing on 27 cities in China found that water bodies play a more significant role in cooling effects in high-latitude, dry areas, suggesting that large water bodies should be considered in park designs for these regions [79]. Table A8 summarizes the findings of studies investigating the impact of background climate on park cooling performance.

3.2.2. Distance from Natural Water Bodies

The proximity of parks to natural water bodies, particularly seas, significantly influences their cooling performance [143]. For instance, in coastal urban areas, such as the Gold Coast in Australia, parks near the sea benefit from sea breezes, which can reduce air temperatures by more than 2 °C in the morning [121]. During the day, sea breezes move inland, cooling the land surface through air exchange. However, at night, the breeze reverses direction, moving from land to sea, and thus does not provide significant cooling effects; in fact, waterfront areas can be slightly warmer at night due to heat release [101,104,123]. This highlights the importance of using trees to block warm land-water breezes at night to maintain cooler temperatures [123].

A study in Shanghai revealed that the distance from the riverbank accounted for 47.65% of a park's cooling effect [139]. Similarly, a study of 117 urban parks in Chengdu, China, found that riverfront parks or those adjacent to lakes exhibited stronger cooling effects, though these parks often had smaller LST differences between the parks and the surrounding water bodies [80]. In Fuzhou, China, greenspaces connected with water bodies, particularly tree-covered areas, were shown to significantly reduce LST and had higher park cooling effects in terms of both extent and intensity [77].

However, not all studies report consistent cooling effects from water bodies. A study in Shanghai found that parks near larger water bodies, such as rivers or seas, exhibited lower cooling performance, possibly because the larger parks are often located further from the water sources [100]. Similarly, research from Zhejiang, China, reported that riverine parks had a smaller mean PCI value (0.66 °C) compared to non-riverside parks (1.59 °C), likely due to the thermoregulatory effects of the adjacent waters [133]. Table A9 summarizes the papers with special attention to the distance of the parks from natural water bodies like rivers and seas.

3.2.3. Urban Configuration and Typology

Research indicates that the cooling effect of parks is influenced by the surrounding urban configuration [93,99,148,149]. Urban configuration and typology refer to the spatial arrangement and characteristics of buildings and other physical structures within a city that have been found to significantly correlate with the cooling effects of green spaces in cities [39,150]. Key variables such as building density—the ratio of the area covered by buildings to the site area—and Floor Area Ratio (FAR), which represents the ratio of a building's total floor area to the site area, along with building height, and building orientation concerning prevailing winds, have been used through studies to evaluate the interaction between surrounding urban area with park's cooling performance [32,148,151].

The PCI generated by vegetation within parks is significantly influenced by the surrounding urban environment [64,152]. Studies in Wroclaw and Shanghai found that parks in less urbanized areas exhibit more substantial cooling effects compared to those in densely built-up regions [63,67]. Similarly, research in Madrid revealed that while large parks provide cooling benefits both within and beyond their boundaries, the cooling performance varies in different park edges considering different urban typologies in each edge [153,154]. The study found that the PCI was higher in edges with an old organic urban structure, due to enhanced wind flow. In contrast, edges with a more structured urban configuration, characterized by higher buildings, exhibited less air temperature reduction and a smaller cooling extension. A study in Beijing further highlighted this variability, showing that cooling extents differed significantly in different directions from the same park, ranging from 35 m to 840 m [55]. This variation can be attributed to the complexity of the surrounding urban configuration, which can influence wind flow and, in turn, affect the cooling performance of the park [154].

However, the extent of cooling provided by urban parks remains a subject of debate across various studies. A study in Melbourne observed that parks near the CBD extend cooling slightly farther than those located at medium or far distances from the city center, likely due to high urbanization and less dense vegetation [36]. Similar findings were reported in Xi'an, China [132]. Another study in Leipzig, Germany, showed a decrease in cooling distance for residential areas with semi-detached housing compared to areas with densely compacted housing [96]. Conversely, a study in Beijing found that the cooling distance from park edges characterized by low building density was significantly greater than from edges with higher building density and complex land cover composition [155].

In Beijing, it was observed that with an increase in building density, PCI gradually increased until building density surpassed a threshold, after which the cooling intensity decreased. This threshold was determined by the anthropogenic heat released by the surrounding neighborhood and the blocking effect of the building morphology [156]. A study in Xi'an, China found that when building density around the green space is between 0.25 and 0.3 (threshold value), the temperature in the buffer zone around the green space decreases the most at more than 1.7 °C [151]. Another study suggested that small green spaces should be planned in areas with high building density, as the cooling intensity of parks was better in these regions [91].

Studies indicate that building height has the strongest correlation with PCI [148,157]. In Hangzhou, China, it was found that the primary reason for increased park cooling effect with building height is the geometry of urban buildings. As building height increases, the ground and buildings are effectively shaded, receiving less solar radiation and stored heat [157]. Similarly, in Changsha, China, increasing building height results in more effective shading, which reduces or delays the impact of direct sunlight on near-surface temperatures, thereby enhancing the cooling effect of green areas [148].

The review of studies showed a complex relationship between FAR and PCI. In Xi'an, China, the research found that the temperature drop range initially increases and then decreases with the increase in FAR in the surrounding built-up area. When FAR is between 2.5 and 3.0, the green space achieves its optimal cooling effect [151]. Another study in Beijing found that as FAR increases, so does the temperature rise, making the cooling effect

of green spaces more significant. However, when FAR exceeds a critical value, the cooling effect of building shadows counteracts the cooling effect of the parks [156].

In the subtropical climate of Hong Kong, a negative relationship was found between building density and FAR with daytime UHI effects, indicating that sites with higher building density and FAR tend to experience lower outdoor air temperatures due to buildings blocking sunlight, which results in lower solar heat gain during the daytime. However, higher building density and FAR can lead to deeper urban canyons and higher nighttime air temperatures due to reduced heat dissipation [32]. In the perimeter of green areas, the reduction in building density and FAR means that the urban space is more open, which is more convenient for the diffusion of the cooling effect of green areas [148].

A simulation-based study found that building orientation has the most significant impact on the park cooling distance, particularly 100 m downwind of the park. The cooling effect of the park is maximized when surrounding buildings are parallel to the prevailing wind direction, resulting in the most intense and widespread park cool island. In contrast, when building orientation is perpendicular to the prevailing wind direction, the park has the shortest cooling distance, with the cooling effect primarily concentrated within 30 m of the park boundary [157]. Table A10 focuses on the findings of studies that specifically examine the influence of surrounding spatial configuration on the cooling performance of urban parks.

4. Discussion

This paper reviewed 131 studies published between January 2014 and July 2024, examining the cooling performance of urban parks worldwide. The review explored both design and site-specific factors that influence the cooling potential of parks, offering insights for designers into how these factors contribute to variations in cooling effectiveness.

Figure 2 illustrates the geographic distribution of the studies, revealing a strong bias toward research conducted in China. Notably, over 60% of the studies were based in China, with Australia and the United States accounting for 8% and 3% of the research, respectively. Additionally, several studies spanned multiple countries rather than focusing on a single location. There are still significant knowledge gaps regarding the cooling performance of urban parks in other regions. For instance, very little is known about parks in the Middle East and North Africa, where arid and semi-arid climates could greatly affect urban livability and thermal comfort. Similarly, there is a lack of research in South America, Africa, and Southeast Asia, regions characterized by tropical climates with high temperatures and humidity, which also significantly impact outdoor thermal comfort. Furthermore, Europe remains underrepresented in this body of research, despite its diverse range of climates, suggesting a need for further studies across these various climatic zones.

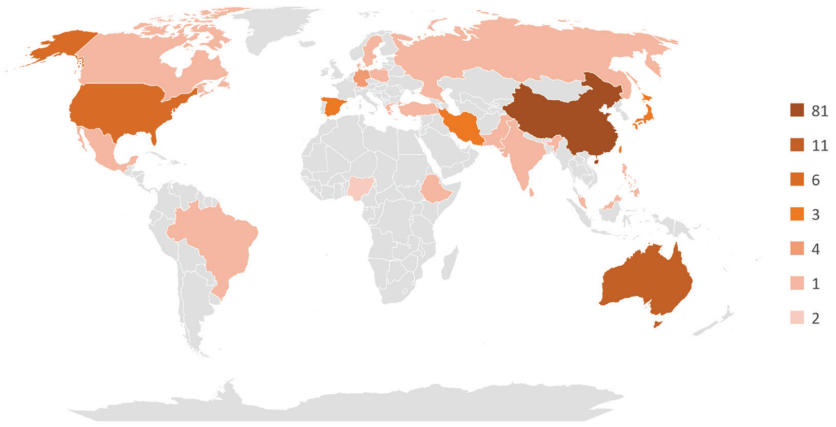


Figure 2. Distribution of studies based on their locations.

4.1. Methodologies for Assessing PCI: Strengths and Limitations

The scale of research varies significantly across studies, which influences the methodologies employed. As shown in Figure 3, the majority of studies (56, or 42%) focused on fewer than 10 parks, with analyses often at the neighborhood scale, allowing for more detailed and accurate analyses of design-related factors both within and around the parks. These studies typically employed methodologies such as field measurements, surveys, and simulations to assess the park's cooling performance. In contrast, as the number of case studies increased and research shifted to the meso and macro scales where larger areas including suburbs or entire cities were examined, researchers often relied on remote sensing data to evaluate general cooling effects. However, this broader approach tended to overlook the detailed features of individual parks. Notably, 47 studies (35%) investigated the cooling performance of parks at the macro scale. While this scale provides a broader perspective, it often lacks clarity on how specific park elements contribute to cooling, leaving gaps in understanding the detailed mechanisms behind urban park cooling performance.

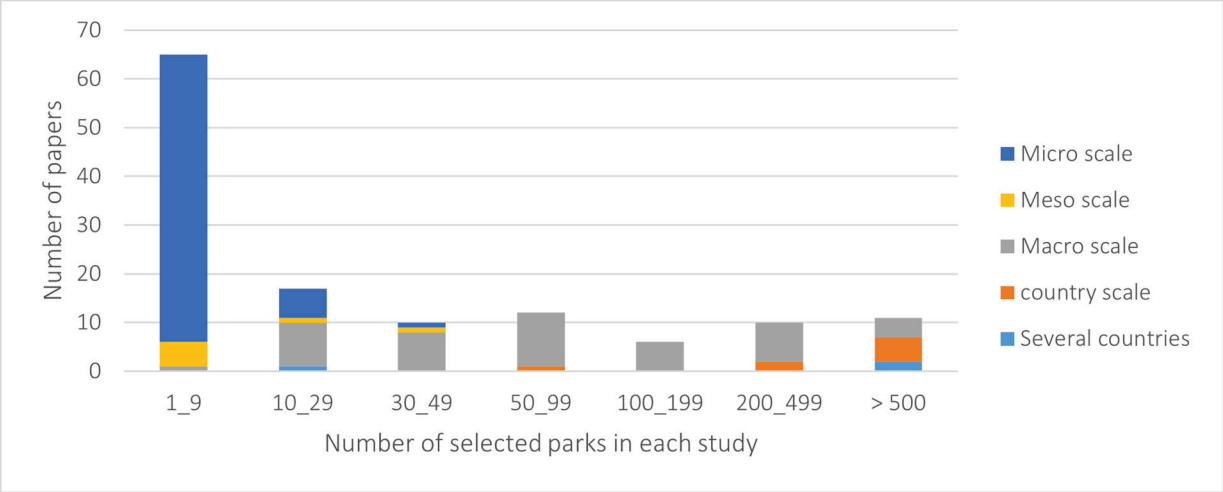


Figure 3. Frequency of studies based on the number of evaluated parks and scope of study.

Data sources used to evaluate park cooling parameters, as shown in Figure 4, varied significantly across studies. Generally, four main methodologies of remote sensing, field measurements, simulation, questionnaires, and surveys have been used to assess the PCI through studies. Remote sensing using satellite images was utilized in 74 studies as the primary data input. Most of these studies focused on meso and macro scales, collecting information from large areas or multiple locations in single snapshots with different resolutions. While remote sensing data offers a wealth of information such as surface-derived indices (such as the normalized difference vegetation index, NDVI), LST, land-use and land-cover classifications, surface fractions, and surface properties, even high-resolution satellite images (30 × 30 m) used by studies are insufficient for capturing the full heterogeneity of vegetated and built-up areas within parks where they coexist. Consequently, this limitation also restricts the efficient analysis of park details. In such cases, park features may be represented by only a few grid cells, where natural and built-up elements are combined, resulting in a significant loss of details. In addition, the satellite images could not provide information about the near-surface layers of parks, making the results inaccurate at the pedestrian level.

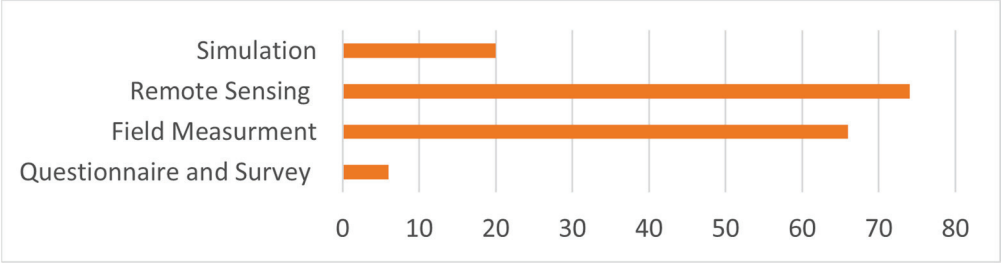


Figure 4. Frequency of data collection methods used in studies.

Although previous research has demonstrated that LST obtained from airborne or satellite-borne thermal infrared images is positively correlated with air temperature and can be considered a suitable indicator for it [158–160], studies have found significant disparities between LST derived from remote sensing and actual air temperature, even when using high-resolution 30 m satellite images [70,71], as surface temperature measurements taken from above the urban canopy; whether from towers or satellites, may underestimate the critical role of shading in the near-surface air layer [37]. This discrepancy highlights the need for future research that integrates both surface and air temperature measurements to fully understand the cooling mechanisms of urban parks. Combining these data sources could provide a more comprehensive view of how parks contribute to cooling and mitigating urban heat.

The second most common methodology for data collection, employed by 45% of studies, is field measurements. These field measurements used three main techniques: fixed, mobile, and handheld data loggers, along with weather stations, to assess cooling performance over specific periods. Fixed weather stations were installed either for short or long-term periods in various locations to monitor variables such as air temperature, relative humidity, and wind speed [37,105,110,136,141,142,149,153]. The placement of these instruments varied depending on research objectives. In some studies, instruments were installed at elevated heights [62,75,101,106,129,136] or on rooftops [37] to prevent vandalism, especially in public spaces. Other studies placed sensors beneath trees, distributed them throughout greenspaces and their immediate surroundings, attached them to poles in streets, or positioned them near vegetated structures [62,75,136].

To enhance spatial coverage, some studies used mobile transects to collect in situ measurements across study areas. These mobile sensors were carried by personnel on foot [33,114,121,122,140,147], mounted on bicycles [37,155], cars [62], or attached to brackets [32,61,84,116–118,120,127,130,137] and backpacks [96] at specific heights above the ground. These sensors were used to measure variables according to the survey's goals, and mobile transects were typically data loggers equipped with global positioning system (GPS) to record the exact time and location of measurements [37,96,155]. Data collection typically occurred on clear, sunny days during periods when the air temperature was highest, often between 8 a.m. and 7 p.m. either continuously [96,107,117,125,130,144] or at specific intervals [45,66,84,111,113,118,124].

The primary aim of these field measurements was to analyze the micro-scale effects of variations in vegetation composition and configuration, species diversity, and the influence of water bodies, as well as the differences in surface cover types such as grass or other materials. In addition to weather data, correlations were conducted between variables to assess the relationship between cooling performance and park features. In some cases, these measurements were used to validate predictive models or to parameterize computer simulations. Field measurements were also occasionally combined with questionnaire surveys to provide a more comprehensive understanding of study objectives, such as thermal comfort perception [83,111,130,153,154], or the alignment of plant community scenes with respondents' environmental preferences [113].

Field measurement studies provide valuable data in real-world settings, offering critical insights into the cooling performance of urban parks. However, such studies often fail

to account for a range of factors that may influence cooling outcomes, thereby limiting their reliability. For instance, research focusing on the cooling effects of specific tree species in parks may overlook variables such as planting configurations (e.g., group versus isolated planting), irrigation rates, and heat hotspots caused by impervious surfaces [110,115,125]. Furthermore, the accuracy of meteorological instruments used in field studies can vary, potentially introducing measurement errors. Considering the advancement in modeling tools, it is recommended to integrate field measurements with them to address these limitations and ensure a more comprehensive evaluation of the factors influencing the cooling performance of urban parks. This approach allows for the comparison and validation of results, ensuring that diverse influencing factors are considered and enhancing the overall robustness of the findings.

As shown in Figure 4, numerical modeling and simulations have been used by 15% of studies to evaluate the influence of design and site-related factors on the cooling performance of urban parks, providing valuable insights across multiple spatial scales. As illustrated in Table 1, among these tools, ENVI-met is the most frequently used, with 15 studies utilizing its micro-scale capabilities to simulate interactions between vegetation, built environments, and atmospheric processes. This makes ENVI-met a cornerstone for analyzing urban microclimates. The software has been applied to assess various factors influencing park cooling performance, such as urban configuration and typology [149,150,157], proximity to water bodies [139,141,143,144], vegetation spatial patterns [88,127,139,140], internal park design scenarios [116,123,137,147], and wind patterns [161]. Meanwhile, RayMan, with its focus on radiative heat transfer and thermal comfort indices, has been used in two studies to evaluate outdoor thermal comfort [88,114].

Table 1. Different models frequently used in the studies.

Models	Simulation Scales	Number of Studies
COSMO	Macro-scale	1
ENVI-met	Micro-scale	15
Fluent	Micro to meso-scale	1
OpenFOAM	Micro to meso-scale	1
RayMan	Micro-scale	2
SOLENE	Micro-scale	1

At larger scales, COSMO, a macro-scale model, has been employed in a study in Moscow to assess the cooling benefits of parks of varying sizes during extreme heat events at the city level [49]. COSMO, a limited-area non-hydrostatic model widely used for numerical weather prediction and regional climate studies, incorporates the TERRA soil active layer scheme and the TERRA_URB bulk urban canopy scheme. However, its largest grid size of 250 $\times$ 250 m may overlook the contributions of smaller parks. In addition, a study used OpenFOAM (V-6) coupled with other software to address its limitations in modeling vegetation impacts on the microclimate [138], while Fluent has been used in combination with field measurements to simulate the effects of real blockages on wind flow [60]. Lastly, SOLENE has been applied in a single study to evaluate the spread of cool air from an urban park [162].

These findings highlight the growing preference for ENVI-met in micro-scale scenario-based simulations, driven by its continuous advancements and expanding capabilities. Over the years, ENVI-met has undergone substantial improvements, making it a highly versatile tool for urban microclimate modeling. Earlier versions, such as version 3, offered simplified plant representations as vegetation columns [163,164]. However, version 4 introduced 3D plant modeling, enabling the detailed digitization of tree crowns and root systems using leaf and root area densities [165]. The latest release, version 5, has further enhanced the model's functionality, incorporating advanced features such as improved

radiative environment calculations, detailed particle flow modeling, and the integration of innovative materials like "super-cool" roofing systems [164–167]. These improvements have significantly enhanced the accuracy and flexibility of ENVI-met, solidifying its position as a leading tool for urban microclimate studies. It is now widely used to simulate the thermal effects of vegetation, as demonstrated in recent studies [168,169].

Simulation software offers valuable opportunities to model scenarios and facilitate comparative analyses in park cooling performance studies. However, these tools often struggle to replicate the complexities of real-world settings accurately. Field measurements have been instrumental in addressing this limitation, providing essential data to validate simulation outputs. For software such as ENVI-met, incorporating field measurements is strongly recommended to ensure that model outputs align with the actual site conditions. Another significant limitation of simulation software lies in its input requirements. Accurately modeling site and design-related factors in parks necessitate comprehensive datasets, which are often unavailable within existing software frameworks. While these tools allow users to create custom datasets for analysis, the accuracy of outputs may still be compromised due to limitations in the foundational data used to develop these manual datasets.

Considering the limitations associated with various methodologies, this study recommends adopting a coupled methodological approach where possible to enhance the accuracy and reliability of findings. By integrating multiple methods, biases inherent in individual approaches can be minimized, leading to more robust and comprehensive results. Such an approach provides valuable insights for landscape architects and policymakers, enabling them to incorporate research findings more effectively into urban design and heat mitigation strategies.

4.2. PCI and PCD Across Different Climates: Findings and Design Implications

The reviewed studies revealed a strong focus on temperate and continental climates, with limited attention to other climate types. The humid subtropical climate (Cfa) accounted for the largest share, with 35 studies (26.7%), followed by the subtropical monsoon climate (Cwa) with 26 studies (19.8%), and the temperate continental monsoon climate (Dwa) with 25 studies (19%). An additional 13 studies (9.9%) focused on the oceanic temperate climate (Cfb). Together, these four climate types represent 75% of all studies, highlighting the considerable academic interest in the cooling effects of urban parks within temperate and continental regions.

In contrast, research on tropical and dry climates remains notably scarce, comprising only 12% of the reviewed studies across all subclasses. This disparity is particularly concerning given the heightened vulnerability of these regions to the adverse impacts of climate change, including increased frequency and intensity of extreme heat events. Several factors contribute to this research gap, including data scarcity, which limits the scope of studies [40,41]; the low cooling potential of UGIs in arid areas due to water scarcity, which reduces their perceived value [170]; and a lack of urgency regarding the use of UGIs in these climates, which further diminishes research and implementation efforts [171,172]. Additionally, limited funding, often influenced by concerns over financial or ecological risks [173–175]; outdated, ambiguous, or conflicting legal and institutional frameworks [176–178], and inadequate cooperation between institutions and urban governance bodies [179] can collectively constrain research progress in these climate zones.

The scarcity of studies in tropical and dry climates creates critical knowledge gaps, particularly in optimizing park design and enhancing thermal comfort in these regions. Moreover, beyond the lack of studies in these specific climates, there is also a substantial gap in understanding how park cooling performance varies across different climate zones. While some studies have focused individually on the cooling effects of parks in specific climates, few studies have systematically examined the critical factors that influence cooling performance across different climatic contexts. Addressing these gaps is essential for developing tailored, region-specific strategies to optimize park design and maximize their

cooling potential. Figure 5 provides a summary of the distribution of studies across the various climate types, illustrating the need for a more balanced research focus.

In tropical climates (Group A), characterized by high temperatures and humidity, studies have reported varying PCI. As shown in Table 2, the highest cooling performance reported in this climate was a temperature reduction of 6.72 °C in Addis Ababa for parks ranging between 0.85 and 22.3 hectares [90]. However, other studies indicate more limited cooling benefits, with temperature reductions typically capped at 3 °C for parks of varying sizes [35,47,53,140,141]. This suggests that parks in tropical climates often fail to deliver extensive cooling benefits, likely due to the region's high humidity levels, which limit transpiration rates and thereby reduce the cooling potential of vegetation.

In Haikou, China, a study reported even lower cooling benefits, with a minimum cooling performance of −2.1 °C for parks larger than 0.09 hectares [47]. This low Mean Park Cooling Intensity (MPCI) could be explained by a high number of small parks functioning as localized heat islands due to inadequate vegetation coverage and suboptimal park design. The disparities may also stem from methodological differences. For instance, the use of low-resolution Landsat images could underestimate park cooling performance compared to in situ measurements, which provide greater accuracy. Additionally, variations in park design factors combined with differences in local air circulation, can influence cooling outcomes in this climate.

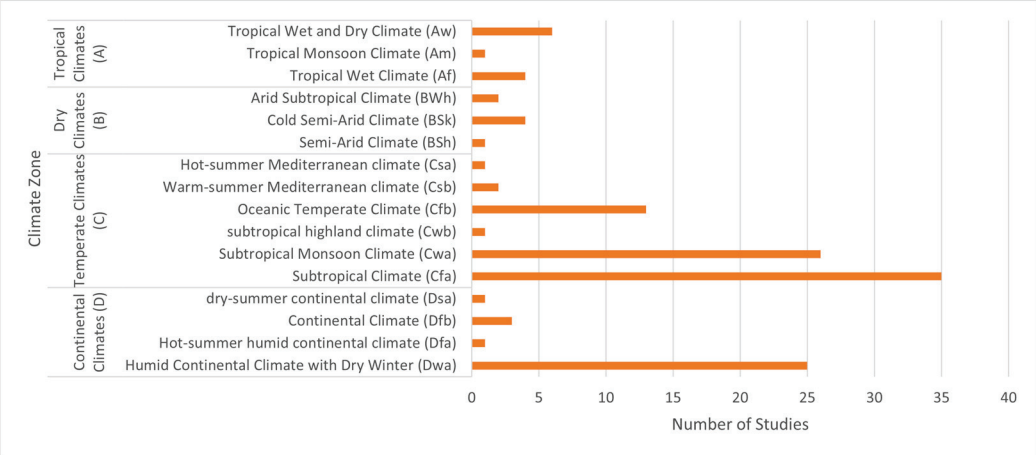


Figure 5. Distribution of studies based on Köppen climate classification.

Table 2. PCI of urban parks in different studies.

	Reference	Location	Climate	Number of Parks	Investigated Range (ha [1])	Mean PCI [2] (°C)
Tropical	[90]	Addis Ababa, Ethiopia	Aw	21	0.85–22.3	0.11–6.72
	[53]	Abuja, Nigeria	Aw	3	2.09–143	0.56–1.6
	[141]	Iloilo City, the Philippines	Aw	N/A [3]	1	0.2–1.95
	[140]	Colombo, Sri Lanka	Af	1	1.95	0.45–2.15
	[35]	Jakarta	Am	82	>0.09	1.8
		Mumbai	Aw	80		1.6
		Singapore	Af	59		1.4
		Kaohsiung	Am	71		2.6
		Kuala Lumpur	Af	75		1.9
		Tainan	Aw	43		3
	[47]	Haikou, China	Aw	152	>0.09	−2.1–0.5

Table 2. *Cont.*

	Reference	Location	Climate	Number of Parks	Investigated Range (ha [1])	Mean PCI [2] (°C)
Arid	[83]	Madrid, Spain	BSk	1	125	0.6–2.8
	[47]	Hohhot, China	BSk	144	>0.09	0.2–2.4
	[81]	29 cities, China	BSk	502	>0.09	2.2–4.2
Temperate	[133]	Zhejiang, China	Cfa	814	<29.25	0–2
	[47]	Shanghai, China	Cfa	191	>0.09	0–2
	[77]	Fuzhou, China	Cfa	435	0.02–296.7	0.35–5.62
	[48]	Changsha, China	Cfa	153	0.27–461.73	−1–6.6
	[59]	Wuhan, China	Cfa	60	9.2–1392.3	3.5
	[100]	Shanghai, China	Cfa	146	N/A	1.57–3.51
	[38]	Wuhan, China	Cfa	40	1.4–324.6	0.08–7.29
	[71]	Shanghai, China	Cfa	41	1.7–3.5	−0.04–3.6
	[91]	Nanjing, China	Cfa	52	1.019–9.663	0–2.61
	[180]	Nanjing, China	Cfa	78	1–20	2.3–4.7
	[51]	Austin	Cfa	49	1.08–116.37	2.93
		Baltimore	Cfa	30	1.17–50.94	3.44
		Chicago	Cfa	67	2.06–149.13	3.72
		Los Angeles	Csb	192	2.07–542.16	4.73
		Portland	Csb	46	1.53–59.85	6.89
	[37]	San Francisco, CA	Csb	1	422	0.9–3.7
	[2]	Copenhagen, Denmark	Cfb	347	0.09–72.02	2.21–3.58
	[106]	Melbourne, Australia	Cfb	1	1.5	0.5–3
	[45]	Melbourne, Australia	Cfb	1	26	0–6
	[95]	Delhi, India	Cwa	15	22.61–1548	0.77–3.62
	[75]	Hong Kong, China	Cwa	14	0.02–525	0.94
	[35]	Hong Kong	Cwa	53	>0.09	0.5
	[46]	Zhengzhou, China	Cwa	123	1.23–108.53	0.64–2.76
	[58]	Port Harcourt, Nigeria	Cwb	4	6.63–90.32	0.36–3.38
	[69]	Athens, Greece	Csa	1	6	3.3–3.8
	[128]	Rome, Italy	Csa	N/A	N/A	1.31
		Florence, Italy				1.14
		Lisbon, Portugal				1.67
		Milan, Italy				1.22
Continental	[128]	Beijing, China	Dwa	N/A	N/A	1.49
		Tianjin, China				1.45
		Tangshan, China				1.15
		Xi'an, China				1.29
	[155]	Beijing, China	Dwa	1	680	0.6–2.8
	[70]	Beijing, China	Dwa	316	5–228	1.7–2.8
	[55]	Beijing, China	Dwa	30	N/A	2.3–4.8
	[84]	Beijing, China	Dwa	10	1–285.25	0.11–2.54
	[135]	Beijing, China	Dwa	1	680	1–3.5
	[47]	Beijing, China	Dwa	277	>0.09	−0.3–1.8
	[129]	Salt Lake Valley (SLV), UT, USA	Dsa	5	9.025–50	1.9
	[50]	Elazı g, Turkey	Dfb	3	1–17	1–3.8
	[81]	29 cities, China	Dfa/Dfb	502	>0.09	2.3–3.9
	[63]	Wroclaw, Poland	Dfb	4	8.84–76.87	2.2–3

[1] ha: Hectare, [2] PCI: Park Cooling Intensity, [3] N/A: Not Applicable.

Desert and semi-arid regions, classified under climate group B, are characterized by average temperatures exceeding 10 °C and minimal rainfall. These low levels of rainfall significantly reduce soil moisture and water availability, both of which are positively correlated with the evapotranspiration rates of vegetation and directly impact the cooling performance of urban parks. Studies focusing on parks in dry climates reported MPCI ranging from 0 °C to 4.2 °C [47,81,83]. While the limited number of studies prevents the establishment of a definitive trend, the findings consistently show that parks in these climates are generally cooler than their surroundings. However, the extent of cooling is often restricted due to extremely high air temperatures during summer.

Extreme heat in arid climates can impair the transpiration rate of vegetation as plants prioritize water preservation and survival mechanisms under heat stress. Consequently, the cooling potential of parks becomes heavily dependent on water availability. Inadequate irrigation systems within parks can severely limit their cooling effectiveness, underscoring the critical role of water management in these arid climates. Moreover, the cooling performance of parks in desert and semi-arid climates is also influenced by the surrounding urban configuration. For example, a study in Madrid reported that cooling effects at different park edges varied between 0.6 °C and 2.8 °C [83]. This variability was attributed to differences in urban form, which impacted wind flow and, consequently, the park's cooling performance.

The majority of studies reporting PCI are concentrated in temperate climates, classified under Group C. These climates are characterized by the coldest month with average temperatures between 0 °C and 18 °C and at least one month averaging above 10 °C. Temperate subclasses exhibit wide variations in precipitation rates during both summer and winter. The findings indicate that maximum MPCI values in the humid subtropical (Cfa) and oceanic temperate (Cfb) subclasses are generally higher than those reported in the monsoonal (Cwa, Cwb) and Mediterranean (Csa) climates. In Cwa and Cwb climates, precipitation peaks during the summer months, resulting in prolonged hot and humid periods. High humidity levels during these periods may reduce the cooling effects of parks by limiting evapotranspiration efficiency. Conversely, in Csa climates, extended dry summers significantly reduce soil moisture, which negatively impacts the cooling performance of vegetation.

Studies reveal a wide range of MPCI values in temperate climates, varying from −1 °C to 7.29 °C. Notably, studies that have observed negative cooling performance in urban parks often focus on parks smaller than two hectares [48,71]. Another consistent trend across studies indicates that as the number of monitored parks increases, the reported MPCI range narrows [2,46,47,133]. This phenomenon can be attributed to the greater number of smaller parks typically included in urban environments. These small parks are mainly located in central business districts, where land availability is limited. These areas are often characterized by high-rise buildings made of heat-retaining materials, which can elevate surrounding temperatures and disrupt wind flow within the parks. Additionally, the prevalence of paved surfaces in such parks contributes to higher land surface temperatures by absorbing more solar radiation. This combination of factors can diminish the cooling performance of these urban parks or even create localized heat islands within the urban landscape.

In addition, small parks located in open, low-rise urban areas are also vulnerable to solar radiation effects due to limited shading from surrounding buildings. In such environments, where buildings are unable to offer adequate shade, and the park size is insufficient to mitigate heat, the solar radiation's elevation and azimuth angles play a critical role in influencing the park's cooling performance. Even in parks shaded by trees, solar radiation can penetrate during the morning and evening hours when the sun is at a lower angle, thereby diminishing the cooling effects. This highlights the importance of considering solar geometry and optimizing tree canopy density and placement to enhance shading throughout the day and improve the park's overall thermal performance.

Continental climates, classified under climate group D, characterized by at least one month averaging below 0 °C and at least one month averaging above 10 °C, have been the focus of several studies. Within this climate class, the subclass Dwa, defined by dry winters and hot summers, has received the most attention. Reported cooling variations in continental climates range from 0 °C to 4 °C, with only one study documenting an MPCI as high as 4.8 °C [55]. This limited cooling performance can be attributed to the extreme temperature fluctuations typical of continental climates, which stress vegetation and diminish its cooling capacity. Additionally, high levels of summer precipitation, particularly in monsoon-influenced Dwa climates, can reduce the cooling impact of parks due to a decreased transpiration rate.

Continental subclasses, such as Dfa (humid continental climates with hot summers), Dfb (humid continental climates with warm summers), and Dfc (subarctic climates with cool summers), generally exhibit higher MPCI values than Dwa climates. These subclasses lack significant seasonal precipitation differences, resulting in consistent humidity levels that support healthier vegetation. This stability can enhance the cooling performance of urban parks compared to the more arid and precipitation-imbalanced Dwa subclass.

Studies on Olympic Park in Beijing, China, from 2018 to 2021 demonstrate temporal PCI variations, with values showing an upward trend [135,155]. The improvements may be attributed to several factors. One possibility is the variation in background temperatures during the study periods, as higher ambient temperatures often improve the cooling effects of parks. Additionally, enhanced irrigation practices likely improved vegetation health and growth during this time, increasing evapotranspiration and, consequently, the PCI.

Overall, PCI fluctuates over time due to a combination of background climate conditions, the surrounding urban environment, park maintenance practices, and vegetation health. These findings highlight the complexity of optimizing cooling performance in urban parks within different climates, where both site and design-related factors play a crucial role. Although existing studies indicate that climate background affects park cooling performance, a clear understanding of how PCI differs across climates is still lacking. More research is needed to assess the cooling performance of urban parks in diverse climates and establish a comprehensive framework for improving their effectiveness under varying conditions.

While most studies focused on PCI, Park Cooling Distance (PCD) is an important factor as it shows the distribution of cooling intensity in the surrounding environment through air convection and heat exchange processes shaping the cooling benefits for nearby areas [39,40]. As shown in Table 3, there is no consistent relationship between PCD and background climate, as parks of similar sizes across different climates often display comparable PCD values. This suggests that PCD is more likely influenced by internal park design features and the surrounding urban form. In dense urban areas, buildings can obstruct wind flow, limiting the spread of cool air and, consequently, the PCD. Therefore, both the layout of park elements and the spatial arrangement of nearby buildings play a critical role in determining the reach of cooling effects. More in-depth studies are needed to clarify how design features and surrounding urban environments influence the cooling performance of parks, and whether these dynamics differ across various climates.

Table 3. PCD of urban parks in different studies.

	Reference	Location	Climate	Number of Parks	Investigated Range (ha [1])	PCD [2] (m)
Tropical	[90]	Addis Ababa, Ethiopia	Aw	21	0.85–22.3	240
Arid	[154]	Madrid, Spain	BSk	1	125	520–600
Temperate	[77]	Fuzhou, China	Cfa	N/A [3]	0.02–296.7	30–180
	[142]	Tokyo, Japan	Cfa	1	0.02	450
	[68]	Shanghai, China	Cfa	24	2.13–143.13	600–800
	[180]	Nanjing, China	Cfa	78	1–20	367–651
	[71]	Shanghai, China	Cfa	41	1.7–3.5	22.6–213
	[51]	Austin	Cfa	49	1.08–116.37	221
		Los Angeles	Cfa	30	1.17–50.94	165
		Chicago	Cfa	67	2.06–149.13	163
		Baltimore	Csb	192	2.07–542.16	116
		Portland	Csb	46	1.53–59.85	132
	[128]	Rome, Italy	Csa	N/A	N/A	130
		Florence, Italy				130
		Lisbon, Portugal				152
		Milan, Italy				138
	[69]	Athens, Greece	Csa	1	6	300
	[2]	Copenhagen, Denmark	Cfb	347	0.09–72.02	105–150
	[36]	Melbourne, Australia	Cfb	27	1–106	0–2217
	[96]	Leipzig, Germany	Cfb	62	0.4–35.6	391–469
	[45]	Melbourne, Australia	Cfb	1	26	860
	[95]	Delhi, India	Cwa	15	22.61–1548	80–300
	[133]	Guangzhou, China	Cwa	10	11.16–192.7	57.84–333.33
Continental	[70]	Beijing, China	Dwa	316	5–228	100–174.4
	[63]	Wroclaw, Poland	Dfb	4	8.84–76.87	110–925
	[128]	Beijing, China	Dwa	N/A	N/A	123
		Tianjin, China				144
		Tangshan, China				132
		Xi'an, China				131
	[155]	Beijing, China	Dwa	N/A	680	1400
	[55]	Beijing, China	Dwa	30	N/A	30–840
	[40]	Xi'an, China	Dwa	65	0.4–339.2	151.4

[1] ha: Hectare, [2] PCD: Park Cooling Distance, [3] N/A: Not Applicable.

4.3. Important Design-Related Parameters for Each Climate Zones

Urban park design must be carefully adapted to the distinct characteristics of each climate zone to maximize the cooling performance and address the environmental challenges unique to each region. In tropical climates (Köppen classification: Group A), where temperatures remain above 18 °C year-round and humidity is high, human thermal comfort is highly sensitive to moisture levels. The excessive humidity in these climates often reduces transpiration efficiency, leading to lower cooling performance of parks in hot, humid cities compared to hot, dry cities [128,132]. To enhance the cooling performance of urban parks in tropical climates, wind flow should be a key design consideration.

While densely planted trees provide effective shading and high levels of evapotranspiration, they can also obstruct airflow, reducing thermal comfort in this climate zone. To address this, strategic design approaches are necessary. For instance, vegetation belts

with dense canopies and elevated crown heights, arranged to minimize crown overlap, can encourage better air circulation. Additionally, designing ventilated corridors aligned with prevailing winds can maintain wind flow, further improving cooling. Adequate spacing between tree crowns is essential to enhance air circulation within parks, improving thermal comfort.

It is also important to minimize internal water bodies, as excessive evaporation can increase humidity and reduce pedestrian comfort in tropical climates. Similarly, large grass-covered areas can negatively impact thermal comfort due to high levels of evapotranspiration. Designers should consider a balanced surface cover, incorporating tree-covered impervious surfaces alongside grass, to maximize cooling benefits and improve overall comfort in tropical urban parks.

Arid and semi-arid regions (Köppen classification: Group B) are characterized by low precipitation and average temperatures around 18 °C. These climates experience high levels of evapotranspiration from vegetation and evaporation from water bodies, contributing to improved cooling performance during hot months. However, cooling performance does not increase indefinitely with rising temperatures. At a certain threshold, extreme heat can reduce the effectiveness of cooling due to limitations in vegetation evapotranspiration [51,104]. While parks in these regions often achieve higher PCI, larger parks are typically required to produce significant cooling effects due to the higher TVoE [97]. Expanding urban parks in arid areas, however, presents notable challenges, particularly due to water scarcity and the reliance on vegetation cooling performance on consistent irrigation.

To optimize cooling in these regions, planners should prioritize the use of trees with large, dense canopies and a high LAI. These features enhance shading and evapotranspiration, mitigating the intense solar radiation common to arid climates. To address the high water demands of vegetation and maintain plant health, landscape designers should select desert-adapted trees and shrubs that are well-suited to local environmental conditions. Grass-dominated landscapes, which demand high levels of irrigation, should be minimized. Unirrigated grass areas can act as heat islands, diminishing the cooling benefits of parks. Instead, a balanced design approach that integrates shrubs and trees alongside limited grass areas can provide shade, protect soil moisture, and improve overall cooling efficiency.

Unlike tropical climates, where wind flow plays a critical role in cooling, arid regions benefit more from strategic vegetation configurations. Group planting of trees is particularly effective in creating shaded microenvironments that enhance thermal comfort. This strategy also mitigates the effects of extreme wind speeds, which can exacerbate overheating in open spaces of arid areas [119,161]. Incorporating water bodies into park designs can also enhance cooling through evaporation. However, given the water scarcity in these regions, small-scale water features are often more practical and sustainable. Additionally, careful selection of impervious surface materials is crucial to minimize solar radiation absorption. Research indicates that surface materials such as cement bricks, grass flagstones, and coconut mats create better human thermal environments compared to baked bricks, polyurethane, and granite [118]. Addressing these challenges requires further field measurements and microscale analyses to identify optimal design strategies for sustainable park development.

In temperate climates (Köppen classification: Group C), characterized by winters with temperatures ranging from 0 to 18 °C and at least one month above 18 °C, parks play a significant role in mitigating the UHI effect, particularly when covered with trees or irrigated grass [128]. Their cooling performance is further enhanced by thoughtful planting strategies that account for seasonal variations and local conditions. A combination of broadleaf deciduous and evergreen trees offers an ideal approach for temperate regions. Deciduous trees with expansive canopies and high LAI provide essential shading during warmer months while allowing sunlight to penetrate in winter, thus balancing seasonal comfort. Meanwhile, evergreen trees contribute to year-round greenery and vibrancy and

can reduce the impact of strong winter winds, as seen in cities like Melbourne, enhancing overall human comfort.

Strategically planting trees in corridors parallel to prevailing summer winds can amplify the cooling effect by facilitating wind flow, thereby distributing cooler air across urban areas. Additionally, targeted tree placement around impervious surfaces, such as roads and paved areas, ensures effective shading, reducing surface temperatures and mitigating localized heat during hot summer months. Water bodies are also another valuable feature in temperate climates, offering significant cooling benefits. Integrating ponds, fountains, or other water features into park designs can lower ambient temperatures and create a more comfortable microclimate, particularly during warmer months. These elements not only enhance the park's esthetic appeal but also improve its functional performance in mitigating heat.

In continental climates (Köppen classification: Group D), characterized by large seasonal temperature variations, urban park designs must be adaptable to both hot summers and cold winters. Deciduous trees play a key role in these regions, providing extensive shade during summer months to reduce heat and allowing solar radiation to penetrate during winter, thereby supporting temperature regulation throughout the year. Utilizing native tree species that are well adapted to the region's wide temperature range is highly recommended for designing climate-resilient parks. Grass-covered areas further enhance cooling during summer through evapotranspiration, effectively lowering surface temperatures when adequately irrigated.

Water features, such as ponds and fountains, offer seasonal benefits and challenges. During extreme heat, they enhance the cooling performance of parks, contributing to a more comfortable microclimate. However, in colder months, these features can lead to chilling effects, adversely impacting thermal comfort. Designers should consider the strategic placement and functionality of water features to balance these seasonal dynamics. Additionally, impervious surfaces, which are unavoidable in urban parks, require careful selection and design in continental climates. Materials must be durable enough to withstand temperature variations during winter and minimize winter hazards caused by icy conditions. Moreover, selecting high-albedo materials for park surfaces can significantly reduce solar radiation absorption during summer, further enhancing cooling performance and thermal comfort.

Table 4 presents the prioritized design-related factors for urban parks across various climate zones, offering a comprehensive overview of the key elements necessary to optimize their cooling performance. The correlation between park size and climate zones shows no significant differences, with larger parks consistently providing superior cooling performance across all climates. However, the TVoE of parks is highly dependent on the climate zones and latitudes where they are located. Studies have reported an MPCI exceeding 5 °C in parks larger than 300 hectares, highlighting the substantial cooling benefits of large parks in specific climatic conditions [38,48,77]. This significant cooling effect is attributed to the stable microclimates created by these parks, driven by their extensive size and dense vegetation coverage. These features enhance cooling performance through evapotranspiration and shading while reducing the influence of surrounding urban environments.

The continuous vegetation cover in large parks reduces wind turbulence, retains cooler air within park boundaries, and minimizes heat intrusion from surrounding built-up areas. Additionally, their size helps maintain consistent cooling effects, regardless of variations in shape complexity. In contrast, smaller parks are more vulnerable to external factors such as urban form, wind flow, and solar radiation, which can significantly influence their cooling performance. For these smaller parks, minimizing shape complexity becomes critical, as excessive fragmentation of green spaces can reduce connectivity, weaken cooling benefits, and increase interaction with the surrounding urban environment.

Table 4. Priorities of design-related factors in different climate zones.

Climate	Design-Related Factors										
			Vegetation characteristics				Vegetation configuration				
			Vegetation species								
	Park Size	Park shape	Turfgrass	Deciduous trees	Ever green trees	LAI	Group planting	Parallel to the prevailing wind	Water bodies	Irrigation	Impervious surfaces
Tropical Climate	-	-	-	-	✓	✓	-	✓	-	-	✓
Arid Climate	✓	-	-	✓	✓	✓	✓	-	✓	✓	✓
Temperate Climate	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Continental Climate	-	-	-	✓	✓	✓	✓	✓	-	✓	✓

5. Conclusions

Rapid urbanization and global warming continue to threaten green infrastructures, particularly urban parks. As cities expand, parks and green areas are increasingly at risk of being replaced by high-rise buildings, diminishing their potential to provide critical ecosystem services. UGIs, particularly parks, not only serve as spaces for recreation and well-being but also play a crucial role in mitigating the devastating impact of extreme heat during hot summers. To maximize the cooling benefits of urban parks, it is essential to focus not only on the design-related factors of parks but also on the site-related variables that influence their cooling performance. This dual approach can guide landscape designers and urban policymakers toward more informed and effective decisions when planning parks and their surroundings.

This study reviewed findings from 131 papers that examined the cooling performance of urban parks across various climate zones. The objective was to categorize these studies based on the design and location-related factors that affect park cooling performance. The findings are summarized as follows:

- Among design-related factors, park size emerged as the most significant determinant of cooling performance, with cooling effects ranging from −2.1 °C to 8.73 °C in studies. However, the cooling efficiency of larger parks is strongly influenced by tree coverage. Large parks with predominantly grass covers can become heat sources if not sufficiently irrigated. In hot and dry climates, the Threshold Value of Efficiency (TVoE) is higher, meaning larger parks are required to achieve similar cooling effects compared to other climates. Proper irrigation and tree coverage are essential to maximize cooling performance in such environments.
- The shape of the park also influences its cooling intensity. In parks ranging from 1 to 20 hectares, those with complex shapes exhibited cooling effects ranging between 2.6 °C and 3.6 °C, while regular-shaped parks provided a wider cooling range of 2.4 °C to 4.7 °C [82]. Round-shaped parks showed the highest PCI, followed by rectangular parks. However, parks with complex boundaries had reduced cooling efficiency due to greater interaction with surrounding land covers, such as buildings and impervious surfaces. Linear parks, in particular, offered the least cooling benefits, with temperature reductions reaching only 0.64 °C in urban areas [46].
- The density and arrangement of trees and vegetation have a substantial impact on the cooling performance of parks across different climates. Isolated tree planting can reduce temperatures by up to 1.8 °C, while linear and group planting configurations offer greater cooling benefits, increasing temperature reductions to 2.33 °C and 3.02 °C, respectively [126]. In high-humidity regions, adequate spacing between tree crowns is

crucial, as it improves air circulation within parks enhancing thermal comfort. Proper vegetation planning, aligned with local climate conditions, can maximize the cooling potential of urban parks.

- Water bodies contribute notably to the cooling performance, particularly in hot and dry climates. The cooling effect of water bodies, driven by evaporation, is most pronounced in close proximity to the water. Additionally, irrigation, which enhances tree evapotranspiration, is crucial, especially in dry areas. Thus, park maintenance is as important as park design in maximizing PCI.
- Climatic factors, such as air temperature, relative humidity, wind speed and direction, and the proximity to water bodies, significantly influence park design factor cooling performance in various climates. Urban planners must consider these environmental conditions from the early stages of park design to optimize cooling performance.
- The surrounding urban form also plays a critical role by influencing wind flow, solar radiation, and the interaction between materials and shortwave radiation. These factors must be carefully evaluated to enhance PCI in urban parks.

Considering the complex interactions between site and design-related factors, it is essential to recognize that park designs cannot be universally applied across different climatic and urban contexts. To achieve optimal outcomes, landscape architects must conduct thorough pre-design field studies. These studies are essential for understanding how site-specific factors influence the effectiveness of design-related factors, enabling the creation of parks with maximized cooling benefits that are tailored to their unique environmental and urban settings.

While considerable progress has been made, key gaps remain in understanding the cooling dynamics of urban parks:

- **Site-specific analyses**, to refine design strategies tailored to distinct climates and urban contexts.
- **Cross-climate comparisons**, to uncover variations in cooling performance across different climate zones.
- **Threshold values for vegetation coverage and water bodies**, providing actionable guidelines for maximizing cooling efficiency in different climates.

Additionally, the reliance on low-resolution satellite imagery in some studies poses a limitation, as it may oversimplify the complex micro-scale cooling dynamics of urban parks. Future research should employ high-resolution remote sensing or field-based methodologies to enhance the accuracy and reliability of findings. Additionally, studies should move beyond descriptive analyses, integrating numerical data and standardized metrics to quantify how specific factors influence PCI.

Considering climate change as a global threat to urban sustainability, it is crucial for governments and policymakers to invest in stronger collaborations with the academic community. By providing incentives and funding for research, they can support the development of practical, evidence-based strategies to promote urban sustainability. Strategic investments in UGI research and effective collaboration enable policymakers to utilize scientific analyses to develop practical frameworks, especially in complex areas such as urban park design, where park cooling performance is strongly shaped by urban characteristics and background climate. Research-driven approaches can reduce risks associated with urban park developments that demand substantial financial investments, ensuring sustainable and impactful outcomes. By fostering such partnerships, cities can prioritize resilient green spaces that benefit ecosystems and communities alike.

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Glossary

CBD	Central Business District
FAR	Floor Area Ratio
GPS	Global Positioning System
LAI	Leaf Area Index
LST	Land Surface Temperature
MPCI	Mean Park Cooling Intensity
MRT	Mean Radiant Temperature
NDVI	Normalized Difference Vegetation Index
PCA	Park Cooling Area
PCD	Park Cooling Distance
PCE	Park Cooling Efficiency
PCI	Park Cool Intensity
PET	Physiological Equivalent Temperature
PH	Position Height
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SVF	Sky View Factor
Smax	Maximum Buffer Area
Spark	Size of the Park
TVoE	Threshold Value of Efficiency
UGI	Urban Green Infrastructure
UHI	Urban Heat Island

Appendix A

Table A1. Studies focusing on the impact of park size on PCI.

Reference	Location	Climate	TVoE [1] (ha)	Investigated Range (ha)	Number of Parks	Mean PCI [2] (°C)
[85]	276 cities, China	NA	0.16–0.42	N/A [3]	13,868	1–4.13
[50]	Elazığ, Turkey	Dfb	N/A		3	1–3.8
[49]	Moscow, Russia	Dfb	N/A	>1	18,678	0.5–1.7
[48]	Changsha, China	Cfa	N/A	0.27–461.73	153	−1.00–6.63
[39]	Zhengzhou, China	Cwa	6–8	N/A	36	0.04–4.61
[80]	Chengdu, China	Cwa	30	>0.09	67	0–4
[87]	Zhengzhou, China	Cwa	8.3	1.25–50.22	28	0.73–5.98
[47]	Hohhot, China	BSk	2.6	>0.09	144	0.2–2.4
	Beijing, China	Dwa	5.9		277	−0.3–1.8
	Shanghai, China	Cfa	4		191	0–2
	Haikou, China	Aw	5.3		152	−2.1–0.5
[78]	276 cities, China	N/A	10	0.1–50	12,720	1.32–1.41
[81]	29 cities, China	BSk	16	>0.09	502	2.2–4.2
		Dfa/Dfb	19			2.3–3.9
[68]	Shanghai, China	Cfa	N/A	2.13–143.13	24	0.36–6.01
[65]	NA, China	Cwa	0.44–0.57	$\overline{A} = 3.33$	30	1.81–3.84
[61]	Hong Kong, China	Cwa	N/A	N/A	2	0.8–4.1

Table A1. *Cont.*

Reference	Location	Climate	TVoE [1] (ha)	Investigated Range (ha)	Number of Parks	Mean PCI [2] (°C)
[51]	Austin	Cfa	5.9	1.08–116.37	384	2.93
	Baltimore		10.3	1.17–50.94		3.44
	Chicago	Dfa	11.3	2.06–149.13		3.72
	Los Angeles	Csb	29.8	2.07–542.16		4.73
	Portland		31.0	1.53–59.85		6.89
[79]	27 cities, China	Dwa	0.81	0.2–94.0	207	0–2
		Cwa	0.71			1–3
		Cfa	0.70			1–3
		Cfa	0.66			2–4
[40]	Xi'an, China	Dwa	N/A	0.4–339.2	65	0.77–1.17
[59]	Wuhan, China	Cfa	N/A	9.2–1392.3	60	3.3–3.7
[33]	Melbourne, Australia	Cfb	N/A	N/A	3	1.69–3.28
[70]	Beijing, China	Dwa	N/A	5–228	316	1.7–2.8
[38]	Wuhan, China	Cfa	N/A	1.4–324.6	40	0.08–7.29
[71]	Shanghai, China	Cfa	N/A	1.7–3.5	41	−0.04–3.6
[58]	Port Harcourt, Nigeria	Cwb	N/A	6.63–90.32	4	1.9–3.58
[75]	Hong Kong, China	Cwa	N/A	0.2–13.06	14	−0.6–4.9
[63]	Wroclaw, Poland	Dfb	N/A	8.84–76.87	4	2–3.6
[91]	Nanjing, China	Cfa	0.384–0.848	1.019–9.663	52	0–2.61
[46]	Zhengzhou, China	Cwa	N/A	1.23–108.53	123	0.64–2.76
[35]	Hong Kong	Cwa	0.60–0.62	>0.09	53	0.5
	Jakarta	Am			82	1.8
	Mumbai	Aw/Am			80	1.6
	Singapore	Af			59	1.4
	Kaohsiung	Am	0.9–0.96		71	2.6
	Kuala Lumpur	Af			75	1.9
	Tainan	Aw			43	3
[82]	Nanjing, China	Cfa	10	0.8–25	2324	2.4–6.82
[76]	Hong Kong, China	Cwa	N/A	0.1–13	14	N/A
[72]	Changzhou, China	Cfa	17	2.52–50.85	18	3.65
[92]	Suzhou, China	Cfa	N/A	2.66–14.37	15	1.34–3.56
[53]	Abuja, Nigeria	Aw	N/A	2.09–143	3	0.56–1.6
[77]	Fuzhou, China	Cfa	N/A	0.02–296.7	435	0.35–5.62
[74]	Changchun, China	Dwa	N/A	0.02–312.13	66	1.1–3.5
[32]	Hong Kong, China	Cwa	N/A	0.077–0.4	12	0.37–1.09
[94]	Shanghai, China	Cfa	40	1–205.32	68	1.32–8.73
[69]	Athens, Greece	Csa	N/A	6	1	3.3–3.8

[1] TVoE: Threshold Value of Efficiency; [2] PCI: Park Cooling Intensity, [3] N/A: Not Applicable.

Table A2. Studies focusing on the impact of park shape on PCI.

Reference	Location	Climate	Investigated Range (ha)	Number of Parks	Mean PCI [1] (°C)
[80]	Chengdu, China	Cwa	>0.09	67	0–4
[49]	Moscow, Russia	Dfb	>1	18,678	0.5–1.7
[48]	Changsha, China	Cfa	0.27–461.73	153	−1.00–6.63
[40]	Xi'an, China	Dwa	0.4–339.2	65	0.77–1.17
[143]	Shanghai, China	Cfa	134–144	3	−0.02–3.7
[58]	Port Harcourt, Nigeria	Cwb	6.63–90.32	4	1.9–3.58
[84]	Beijing, China	Dwa	15.21–285.2	10	0.11–2.54
[100]	Shanghai, China	Cfa	N/A [2]	146	1.1–6.1
[2]	Copenhagen, Denmark	Cfb	0.09–72.02	301	2.21–3.58
[91]	Nanjing, China	Cfa	1.019–9.663	52	0.532
[46]	Zhengzhou, China	Cwa	1.23–108.53	123	0.64–2.76
[82]	Nanjing, China	Cfa	1–20	78	2.4–4.7
[95]	Delhi, India	Cwa	17.37–1548	15	0.77–3.62
[53]	Abuja, Nigeria	Aw	2.09–143	3	0.56–1.6
[92]	Suzhou, China	Cfa	2.66–14.37	15	1.34–3.56
[72]	Changzhou, China	Cfa	2.52–50.85	18	3.65
[77]	Fuzhou, China	Cfa	0.02–296.7	435	0.35–5.62
[94]	Shanghai, China	Cfa	1–205.32	68	1.32–8.73
[134]	Beijing, China	Dwa	42–297	4	1.48–2.72
[96]	Leipzig, Germany	Cfb	0.4–35.6	62	0–3.4
[90]	Addis Ababa, Ethiopia	Aw	0.85–22.3	21	0.11–6.72

[1] PCI: Park Cooling Intensity. [2] N/A: Not Applicable.

Table A3. Studies focusing on the impact of vegetation on PCI.

Reference	Location	Climate	Main Focus	Investigated Range (ha)	Number of Parks	Mean PCI [1] (°C)
[97]	Beijing, China	Dwa	Crown structure	0.9–32.3	9	2.71 ± 1.52
[109]	Shanghai, China	Cfa	Crown structure	27.85–60.5	5	0.33–3.8
[115]	Changchun, China	Dwa	Coniferous trees	142	1	0.82–3.24
			Broad-leaved trees			1.8–3.38
[37]	San Francisco, CA, USA	Csb	Grass	422	1	0.9–2.6
			Tree			1.9–37
[121]	Gold Coast, Australia	Cfa	LAI	N/A [2]	18	−1.5–0.5
[110]	Haitan Island, China	Cwa	Coniferous trees	N/A	1	1.4
			Deciduous broad-leaf Trees			1.31
			Evergreen broad-leaf Trees			1.3
			Palm trees			0.93
[117]	Wuhan, China	Cfb	Grass	N/A	20	2.8
			Trees			6.1

Table A3. *Cont.*

Reference	Location	Climate	Main Focus	Investigated Range (ha)	Number of Parks	Mean PCI [1] (°C)
[105]	Leipzig, Germany	Cfb	Tree and grass	5.8–17.5	2	0.1–0.39
[61]	Hong Kong, China	Cwa	Trees	N/A	2	0.8–4.1
[122]	Xindu, China	Cwa	Increasing SVF by 0.1	N/A	2	1
			Increasing LAI by 1			2.5
[108]	Changzhou, China	Cfa	Crown structure	N/A	15	2.9–4.6
[129]	Salt Lake Valley, UT, USA	Dsa	Vegetation type	9–50	5	1.1–3.3
[112]	Gold Coast, Australia	Cfa	Crown structure	N/A	2	0.67–0.8
[123]	Chongqing, China	Cwa	Increasing LAI by 1	160	1	0.19–0.31
[106]	Melbourne, Australia	Cfb	SVF	1.5	1	0.5–3
[127]	Tabriz, Iran	Bsk	Deciduous trees	N/A	1	2
			Evergreen trees			1.2
[124]	Gold Coast, Australia	Cfa	SVF	N/A	18	2–2.5
[113]	Shanghai, China	Cfa	Crown structure	4.3	1	1.23–2.42
[88]	Berlin, Germany	Cfb	Vegetation type	355	1	1.2–4.3
[107]	Beijing, China	Dwa	Vegetation type	760	1	0.48–1.12
[125]	Taiwanese, Taiwan	Cwa	Crown structure	N/A	1	N/A
[66]	Beijing, China	Dwa	Tree species	4.5	1	0.5–1.6
[120]	Beijing, China	Dwa	Crown structure	680	1	1–5

[1] PCI: Park Cooling Intensity, [2] N/A: Not Applicable.

Table A4. Studies focusing on the impact of vegetation coverage and their spatial arrangement on PCI.

Reference	Location	Climate	Main Focus	Investigated Range (ha)	Number of Parks	Mean PCI [1] (°C)
[139]	Shanghai, China	Cfa	Planting configuration	N/A [2]	5	N/A
[137]	Xi'an, China	Dwa	Vegetation density	16.8	1	N/A
[140]	Colombo, Sri Lanka	Af	Planting configuration	1.95	1	0.45–2.15
[143]	Shanghai, China	Cfa	Planting configuration	134–144	3	−0.02–3.7
[63]	Wroclaw, Poland	Dfb	Vegetation density	8.84–76.87	4	2–3.6
[126]	Xi'an, China	Dwa	Isolated planting	N/A	2	1.02 ± 0.78
			Linear planting			1.37 ± 0.96
			Group planting			2.05 ± 0.97
[127]	Tabriz, Iran	Bsk	Rectangular planting	N/A	1	1.8–2.2
			Triangular planting			1.5
[95]	Delhi, India	Cwa	Vegetation density	17.37–1548.43	15	0.77–3.62
[88]	Berlin, Germany	Cfb	Planting configuration	355	1	1.2–4.3
[136]	Curitiba, Brazil	Cfb	Vegetation density	N/A	15	N/A
[89]	Nanjing, China	Cfa	Vegetation density	N/A	116	0.6–6.9
[131]	Nanjing, China	Cfa	Planting configuration	N/A	808	

[1] PCI: Park Cooling Intensity, [2] N/A: Not Applicable.

Table A5. Studies focusing on the impact of internal water bodies on PCI.

Reference	Location	Climate	Main Focus	Investigated Range (ha)	Number of Parks	Mean PCI [1] (°C)
[137]	Xi'an, China	Dwa	Park design factors	16.8	1	N/A [2]
[133]	Guangzhou, China	Cwa	Wetland parks	11.16–192.7	10	1.15–4.02
[48]	Changsha, China	Cfa	Park design factors	0.27–461.73	153	−1.00–6.63
[68]	Shanghai, China	Cfa	Park design factors	2.13–143.13	24	0.36–6.01
[59]	Wuhan, China	Cfa	Park design factors	9.2–1392.3	60	3.3–3.7
[2]	Copenhagen, Denmark	Cfb	Park design factors	0.09–72.02	347	2.21–5.26
[144]	Beijing, China	Dwa	Park water body cooling	0.38	1	1.3
[92]	Suzhou, China	Cfa	Park design factors	2.66–14.37	15	1.34–3.56

[1] PCI: Park Cooling Intensity, [2] N/A: Not Applicable.

Table A6. Studies focusing on the impact of irrigation on PCI.

Reference	Location	Climate	Main Focus	Investigated Range (ha)	Number of Patches	Mean PCI [1] (°C)
[146]	Hamburg, Germany	Cfb	Soil texture	>0.09	N/A [2]	1.5–5
[129]	Salt Lake Valley, UT, USA	Dsa	Vegetation type	9–50	5	1.1–3.3
[56]	Puebla, Mexico	Cwb	Park design factors	0.07–156.3	68	N/A
[128]	Beijing, China	Dwa	Cross climate cooling asses	N/A	N/A	1.49
	Tianjin, China					1.45
	Tangshan, China					1.15
	Xi'an, China					1.29
	Rome, Italy	Csa				1.31
	Florence, Italy					1.14
	Lisbon, Portugal					1.67
	Milan, Italy					1.22
[145]	San Francisco, CA, USA	Csb	Seasonal vegetation greenness	0.032–200	135	N/A
[107]	Beijing, China	Dwa	Vegetation type	760	1	0.48–1.12
[119]	Kuala Lumpur, Malaysia	Af	Elements impacting PCI	N/A	N/A	1–6
	Kuala Lumpur, Malaysia	Bsh				
	Alice Springs, Australia	BWh				
	Kyoto, Japan	Cfa				
	Toronto, Canada	Dfa				

[1] PCI: Park Cooling Intensity, [2] N/A: Not Applicable.

Table A7. Studies focusing on the impact of impervious surfaces on PCI.

Reference	Location	Climate	Main Focus	Investigated Range (ha)	Number of Parks	Mean PCI [1] (°C)
[56]	Puebla, Mexico	Cwb	Park design factors	0.07–156.3	68	N/A [2]
[118]	Suwon, Republic of Korea	Dwa	Surface materials	N/A	1	1.5
[116]	Tehran, Iran	Bsk	Surface albedo	N/A	1	0.2–0.6
[76]	Hong Kong, China	Cwa	Park design factors	0.1–13	14	N/A
[92]	Suzhou, China	Cfa	Park design factors	2.66–14.37	15	1.34–3.56
[147]	Seoul, Republic of Korea	Dwa	Surface materials	N/A	1	1.3–4.1

[1] PCI: Park Cooling Intensity, [2] N/A: Not Applicable.

Table A8. Studies focusing on the impact of background climate on PCI.

Reference	Location	Climate	Main Focus	Investigated Range (ha)	Number of Patches	Mean PCI [1] (°C)
[47]	Hohhot, China	BSk	Cross climate cooling assessment	>0.09	144	0.2–2.4
	Beijing, China	Dwa			277	−0.3–1.8
	Shanghai, China	Cfa			191	0–2
	Haikou, China	Aw			152	−2.1–0.5
[78]	276 cities, China	NA	Cross climate cooling assessment	0.1–50	12,720	1.32–1.41
[81]	29 cities, China	NA	Cross climate cooling assessment	3.11–203.13	502	N/A [2]
[79]	27 cities, China	Dwa	Cross climate cooling assessment	0.2–94.0	207	0–2
		Cwa				1–3
		Cfa				1–3
		Cfa				2–4
[75]	Hong Kong, China	Cwa	Park design factors	0.2–13.06	14	−0.6–4.9
[76]	Hong Kong, China	Cwa	Park design factors	0.1–13	14	N/A
[128]	Beijing, China	Dwa	Cross climate cooling assessment	N/A	N/A	1.49
	Tianjin, China					1.45
	Tangshan, China					1.15
	Xi'an, China					1.29
	Rome, Italy	Csa				1.31
	Florence, Italy					1.14
	Lisbon, Portugal					1.67
	Milan, Italy					1.22

[1] PCI: Park Cooling Intensity, [2] N/A: Not Applicable.

Table A9. Studies focusing on the impact of natural water bodies on PCI.

Reference	Location	Climate	Main Focus	Investigated Range (ha)	Number of Patches	Mean PCI [1] (°C)
[133]	Guangzhou, China	Cwa	Wetland parks	11.16–192.7	10	1.15–4.02
[80]	Chengdu, China	Cwa	Internal and external factors impacting PCI	>0.09	67	0–4
[121]	Gold Coast, Australia	Cfa	Distance from the sea	N/A [2]	18	2–2.5
[100]	Shanghai, China	Cfa	Internal and external factors impacting PCI	N/A	146	1.1–6.1
[143]	Shanghai, China	Cfa	Riverine parks	134–144	3	−0.02–3.7
[141]	Iloilo City, the Philippines	Aw	Riverine parks	N/A	1	0.2–1.95
[123]	Chongqing, China	Cwa	Increasing LAI by 1	160	1	0.19–0.31
[77]	Fuzhou, China	Cfa	Internal and external factors impacting PCI	0.02–296.7	435	0.35–5.62

[1] PCI: Park Cooling Intensity, [2] N/A: Not Applicable.

Table A10. Studies focusing on the impact of urban configuration on PCI.

Reference	Location	Climate	Main Focus	Investigated Range (ha)	Number of Patches	Mean PCI [1] (°C)
[67]	Shanghai, China	Cfa	Local Climate Zone (LCZ)	N/A [2]	484	0.11–6
[149]	Beijing, China	Dwa	Spatial morphology	1.82	1	1
[148]	Changsha, China	Cfa	Spatial morphology	N/A	40	1–1.7
[150]	Melbourne, Australia	Cfb	Spatial morphology	N/A	3	N/A
[132]	Xi'an, China	Dwa	Internal and external factors impacting PCI	N/A	59	N/A
[156]	Beijing, China	Dwa	Spatial Morphology	>0.09	797	0.27–1.7
[157]	Hangzhou, China	Cfa	Building orientation	1.08	1	0.19–1.24
[99]	Beijing, China	Dwa	Internal and external factors impacting PCI	0.5–238.08	70	N/A
[39]	Zhengzhou, China	Cwa	Internal and external factors impacting PCI	N/A	36	0.04–4.61
[151]	Xi'an, China	Dwa	Spatial morphology	1.3–34.2	36	0.68–1.7
[64]	Beijing, China	Dwa	LCZs	N/A	143	2.63–3.34
[152]	Dallas, TX, USA	Cfa	land-use/land cover classifications	N/A	1201	1.6–2.7
[63]	Wroclaw, Poland	Dfb	Building density	8.84–76.87	4	2–3.6
[91]	Nanjing, China	Cfa	Building density	1.019–9.663	52	0–2.61
[153]	Madrid, Spain	Bsk	Spatial morphology	125	1	0.9–1.6
[154]	Madrid, Spain	Bsk	Spatial morphology	125	1	2.4–2.8
[36]	Melbourne, Australia	Cfb	Distance from CBD on PCI	1–106	27	3–10
[155]	Beijing, China	Dwa	Internal and external factors impacting PCI	680	1	0.6–2.8
[96]	Leipzig, Germany	Cfb	Internal and external factors impacting PCI	0.4–35.6	62	0–3.4
[55]	Beijing, China	Dwa	Spatial morphology	N/A	30	2.3–4.8

[1] PCI: Park Cooling Intensity, [2] N/A: Not Applicable.

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Evaluating the Impact of Oil Refinery on Landscape Values Perception and Mental Health: A Case Study of Tehran

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Abstract: In today's society, stress is recognized as a major contributor to illness. It can be reduced through exercise, which lowers stress hormones, and exposure to daylight, which regulates hormones such as cortisol and melatonin. Furthermore, the design and perception of the environment can indicate danger or safety, influencing stress levels and mental health. This study examines the Tehran Oil Refinery's impact on local residents' perceptions of landscape values and mental health. Oil refineries, which use compounds derived from natural gas or crude oil, pose both short- and long-term environmental and health risks. Using a Geographic Information System for Public Participation (PPGIS), the study investigates how the industrial landscape surrounding the Tehran Oil Refinery influences residents' emotional responses and stress levels. The study collects sociodemographic data, self-perceived health data, and landscape valuations before and after photography interventions. The findings indicate a complex relationship between the refinery's presence and perceptions of landscape values. Manipulated photographs used in the study show how visual elements can influence emotional responses, highlighting a direct link between stress and environmental perception. This case study adds to larger discussions about the effects of industrialization on public mental health and the environment, emphasizing the importance of incorporating public perception into urban planning in order to achieve sustainable development.

Keywords: participatory process; industrial clusters; landscape perception; stress

1. Introduction

Today, stress is regarded as one of the most critical factors related to ill health in modern society. Stress reactions may be reduced with exercise, which rids the body of some of the fighting and wakefulness hormones. Exposure to daylight may reduce stress reactions by adjusting hormone levels, especially cortisol and melatonin. Moreover, the environment's design may signal danger or safety [1].

Understanding the relationship between the urban environment and health, particularly the benefits of the outdoors for mental health, is becoming increasingly important [2–4]. This is why urban planners and architects must consider the built environment's impact on stress levels. By incorporating landscape values such as green spaces, natural light, and opportunities for physical activity, they can help create environments that promote relaxation and well-being. According to Ulrich et al. (1991), different conceptual perspectives suggest that natural environments reduce stress and promote recovery, while urban environments hinder recuperation. The psycho-evolutionary theory posits that these restorative effects

involve positive shifts in emotional states, physiological changes, and sustained attention. Their research found that individuals exposed to natural settings after a stressful stimulus experienced faster recovery, as indicated by physiological and self-reported measures, than those exposed to urban environments. This supports the notion that the characteristics of an environment—such as the presence of nature versus human-made elements—play a crucial role in influencing stress recovery and mental well-being [5].

Several studies have focused on landscape values and stress. Grahn and Stigsdotter [1] investigated how city landscape planning could affect residents' health. They found statistically significant associations between using urban open green spaces and self-reported stress experiences regardless of the informant's age, gender, or socioeconomic status. The study found that the more often a person visits urban open green spaces, the less likely he or she is to report stress-related illnesses. Skärbäck [6] explored the balance between nature and landscape values in development planning, focusing on measures to mitigate negative impacts. This research aimed to raise awareness among the public, developers, and politicians about improving health as a parameter for sustainable development. Thompson et al. [7] discovered that salivary cortisol can be used as a biomarker to assess stress levels associated with green space exposure. Their research discovered significant links between self-reported stress, cortisol secretion patterns, and green space quantity in the living environment. The percentage of green space in the living environment significantly predicted the circadian cortisol cycle and self-reported physical activity. Van den Berg et al. [8] explored the potential of green space to mitigate the negative health effects of stressful life events. They found that respondents with more green space were less affected by stressful life events. Stigsdotter et al. [9] investigated the associations between green space and health, health-related quality of life, and stress, respectively. They found that respondents living one kilometer away from green spaces report poorer health and quality of life and have 1.42 times more chances of experiencing stress compared to those living closer. Grahn and Stigsdotter [10] found a relationship between sensory perception of natural environments and human health. They identified eight perceived sensory dimensions: Serene, Space, Nature, Rich in Species, Refuge, Culture, Prospect, and Social. People prefer Serene, followed by Space, Nature, Rich in Species, Refuge, Culture, Prospect, and Social. Refuge and nature were found to be most strongly correlated with stress, suggesting the need for restorative environments. This indicates that individuals often seek these environments for stress relief, highlighting their importance as restorative spaces. Lottrup, Grahn, and Stigsdotter [11] investigated the relationship between access to green outdoor environments at work and employees' perceived stress and attitude toward the workplace. Data showed a significant relationship between physical and visual access to greenery, a positive workplace attitude and decreased stress for male respondents. Female respondents showed a similar relationship but not between access and stress. Vujcic et al. [12] found that green spaces are suitable settings for running and jogging, and they may alleviate self-reported nervous problems and medication use. Shu et al. [13] investigated the restorative effects of virtual nature on anxiety, depression, and stress in patients with depression. It found that landscape type, viewing distance, and permeability significantly influence these effects. Studies showed that environments with higher openness, green elements, blue sky, and sunshine exposure had higher restorative levels. Grassland landscapes with higher viewing distances showed more restorative impacts. Ha et al. [14] investigated the relationship between urban green space and mental health in Chicago, focusing on the spatial distribution of green spaces. They found that residents reported less psychological distress in urban landscapes with small-sized water bodies and greater distances between forested areas. However, psychological distress levels were lower in landscapes with a

disaggregated distribution of green spaces, suggesting that the configuration of urban green space may be as important as the amount of green space.

1.1. Explaining Case Study

The Tehran Oil Refinery (Figure 1), located south of Tehran, is one of Iran's most important oil-producing facilities. It was built between 1965 and 1968, with the south refinery becoming operational in 1969 and the north refinery in 1973. The refinery is still fully operational today, playing an important role in the country's oil production. The refinery produces many petroleum and chemical products, including liquid gas, regular gasoline, light and heavy naphtha, kerosene, gas oil, furnace oil, and mineral oil. The Tehran refinery produces 11% gasoline, 34% gas oil, 21% furnace oil, and 2% other products, accounting for approximately 12% of Iran's total refining capacity [15]. Air pollution is a primary environmental concern at this refinery because it emits particulate matter, volatile organic compounds, NOx, SOx, and other harmful pollutants that endanger both human health and the environment.

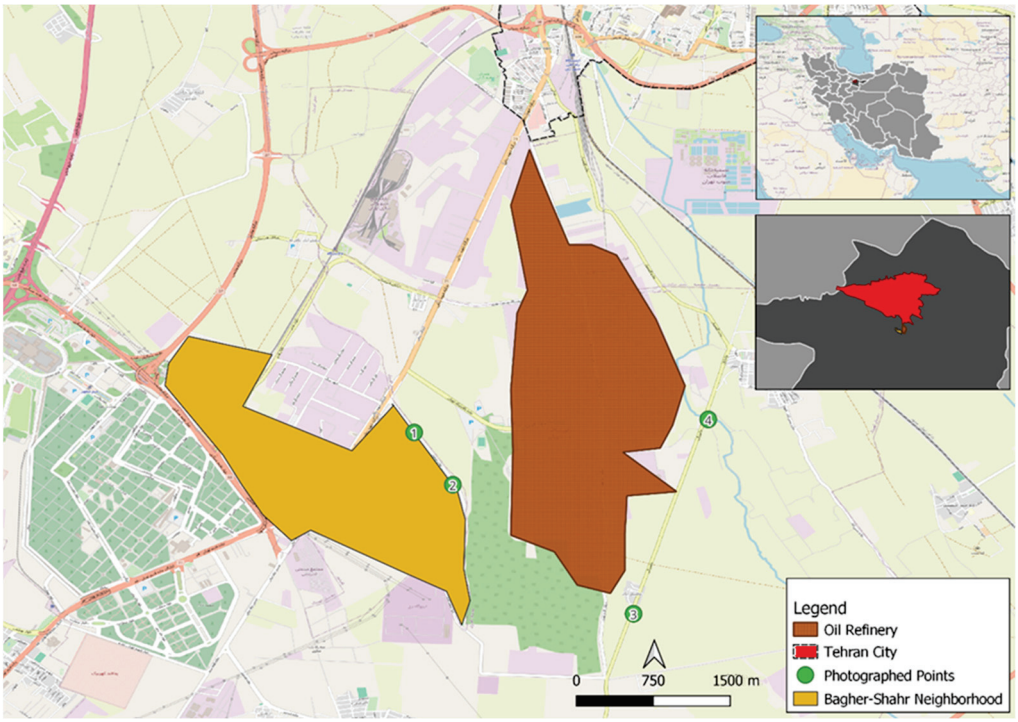


Figure 1. Case study Location and surroundings.

1.2. Problem Statement

Industrial areas, particularly petrochemical plants and oil refineries, pose significant environmental and social challenges to nearby populations, including both short- and long-term risks to public health and the environment. However, the extent to which these industrial presences affect local residents' emotional and psychological well-being remains underexplored. This study aims to address this gap by using an online participatory survey combined with a Public Participation Geographic Information System (PPGIS) to investigate how residents perceive landscape values in areas near the Tehran Oil Refinery and surrounding industrial complexes. The primary objectives of the study are outlined below:

- To assess the perception of landscape values near the Tehran Oil Refinery.
- To examine the relationship between landscape value perceptions and stress levels among local residents.

By exploring how oil refineries influence perceptions of landscape values in Tehran, this study seeks to offer policymakers and stakeholders critical insights into industrial clusters' strategic planning and design, ultimately aiming to mitigate their adverse impacts on human health.

2. Materials and Methods

The term PPGIS was first used in 1996 at the National Center for Geographic Information and Analysis meetings in the United States, and its relevance has been emphasized repeatedly [16]. There are various methods for analyzing landscape values and stress levels. For example, one of the most recent participatory methods is public participation geographic information (PPGIS), which is a system used in various landscape value studies [17–21]. In addition, participatory methods were used in various stress and well-being studies on an urban scale [22,23]. This study integrates PPGIS by combining geographic data with public perceptions of landscape values and mental health. The methodology includes the spatial mapping of respondents' perceptions using a participatory survey design incorporating geolocated data points. These data are analyzed in relation to the proximity to the Tehran Oil Refinery, thus grounding the study in a spatial and participatory framework.

Design of the Survey

The survey was eight pages long, written in Farsi language, and designed to be completed online. It was conducted online using the Porsall (https://porsall.com/, accessed on 6 August 2023) platform, allowing efficient and organized data collection. To ensure a diverse sample of participants, the researchers distributed the questionnaire via various channels, including popular social media platforms such as LinkedIn, WhatsApp groups, and Telegram channels. Furthermore, some surveys were completed in person, ensuring that people who had difficulty accessing the Internet were not excluded. The questionnaire was standardized across all formats to ensure data compatibility between LinkedIn, WhatsApp, Telegram, and in-person surveys with responses integrated into a unified database. Ethical considerations, including informed consent and participant confidentiality, were reviewed and approved by an Institutional Review Board (IRB) prior to survey administration.

The first section of the survey focused on mental health, specifically exploring how participants perceived stress arising from the presence of the Oil Refinery. The stress level was designed based on the Perceived Stress Scale provided by Cohen, Kamarck, and Mermelstein [24]. Despite its age, the PSS remains a popular method for evaluating how various situations influence feelings of stress. The scale's questions probe into individuals' thoughts and emotions. In this study, the short version of the scale, known as the PSS-4, was used. Participants were asked how frequently they experienced certain feelings or thoughts over the past month [25]. The following questions were treated individually:

1. How often have you felt that you were unable to control the important things in your life?
2. How often have you felt confident about your ability to handle your personal problems?
3. How often have you felt that things were going your way?
4. How often have you felt difficulties piling up so high that you could not overcome them?

In the second section, participants were asked about their perceptions of landscape values using both original and edited photographs (Figure 2). This section was conceived considering a previous work conducted by Svobodova et al. [26], where the authors selected photographs based on the visibility of an oil refinery and people's awareness.



Figure 2. A screenshot of the online survey. (Translation: What are your feelings when you are going to study, listen to music, or do physical activity in this certain place?).

The four locations for photographs were carefully selected based on their representativeness of the area surrounding the Tehran Oil Refinery (Figure 3). The criteria for choosing these locations included proximity to residential areas, visibility of industrial elements, and environmental variation. Specifically, two locations were on the border between the Tehran Oil Refinery and the Bagher–Shahr Neighborhood to capture the interface between industrial and residential zones, while the other two were to the east of the refinery to offer different environmental perspectives. The photographs taken at these locations were then manipulated to assess the impact of industrial elements on participants' perceptions. In three of the photographs (1, 3, and 4), the presence of the oil refinery and surrounding

industrial areas was minimized by enhancing natural elements like greenery and open sky. In contrast, photograph 2 emphasizes the industrial presence by including additional refinery smoke, fires, and intensified pollution indicators. These changes enabled a comparative analysis of how different levels of industrial visibility influence landscape perception and the resulting emotional and psychological responses.

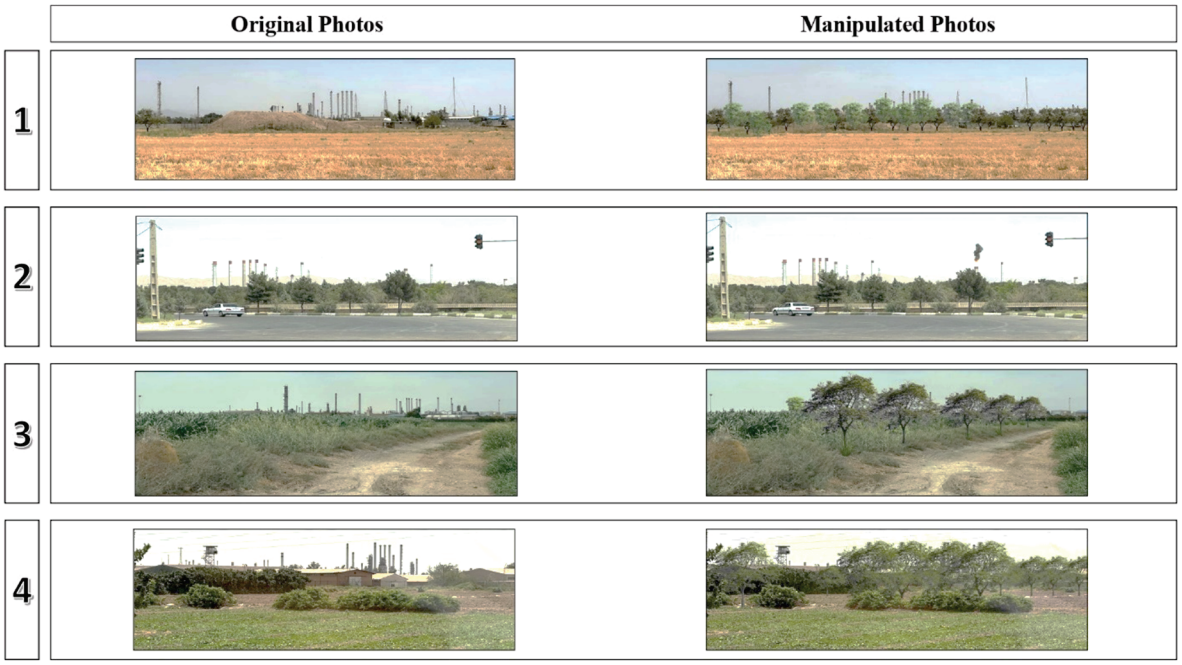


Figure 3. Photographs captured at selected points.

Following that, the perception of landscape values was assessed using photographs, and participants were asked to use a set of adjectives for both original and manipulated photographs. Regarding the landscape values perception questions, participants were asked how they felt about the photographs while doing sports, reading, or walking in those areas. The adjectives were used according to the following three groups (Table 1):

1. Anxious/Serene;
2. Restless/Tranquil;
3. Tense/Calm.

Table 1. Adjectives description (Source: [27]).

Adjectives	Description
Anxious	feeling or showing worry, nervousness, or unease about something with an uncertain outcome.
Serene	peaceful and calm; worried by nothing.
Restless	unwilling or unable to stay still or to be quiet and calm, because you are worried or bored.
Tranquil	calm and peaceful and without noise, violence and worry.
Tense	nervous and worried and unable to relax.
Calm	peaceful, quiet, and without worry.

Finally, the third section included a demographic and social section to collect important information about the respondents. This section included information about age, gender, place of residence, level of education, and income.

3. Results

3.1. Social–Demographic Findings

The participatory process involved a total of 220 participants. Eighty percent of responses were collected via online survey, and the rest were collected via interview. Also, one response was eliminated due to incorrect information. Females account for 52.27% of all respondents, while males make up 45.45% (Table 2). The 25–34 age group is the most represented (31.36%), which is followed by the 16–24 and 35–44 age groups. The data also show decreased participation among respondents aged 45 and older.

Table 2. Informant characteristics.

Age Group	Female	Male	N/A	Total
N/A	8.18%	9.09%	1.36%	18.64%
16–24 years	14.55%	7.73%	0.45%	22.73%
25–34 years	16.82%	14.55%	0.00%	31.36%
35–44 years	7.27%	10.00%	0.00%	17.27%
45–54 years	2.73%	1.82%	0.45%	5.00%
More than 55 years	2.73%	2.27%	0.00%	5.00%
Total	52.27%	45.45%	2.27%	100.00%

3.2. Perceived Stress Scale

Table 3 shows the Perceived Stress Scale distribution of respondents. The perceived stress scale evaluates the self-reported amount of stress in the participants by assessing thoughts and feelings in the previous month.

Table 3. Perceived Stress Scale distribution of respondents.

Score	PSS-1	PSS-4	Score	PSS-2	PSS-3
Never (0)	16.82%	20.45%	Never (4)	14.09%	10.00%
Almost Never (1)	20.00%	20.91%	Almost Never (3)	31.36%	43.18%
Sometimes (2)	8.64%	10.00%	Sometimes (2)	6.36%	4.09%
Fairly Often (3)	50.91%	44.55%	Fairly Often (1)	45.00%	34.55%
Very Often (4)	3.64%	4.09%	Very Often (0)	3.18%	8.18%
Total	100%	100%	Total	100%	100%

After calculating the total scores for the Perceived Stress Scale (PSS), the scores were categorized into four levels to enhance readability. The categories are defined as follows:

- Low Stress: 0–4;
- Medium Stress: 5–8;
- High Stress: 9–12;
- Very High Stress: 13–16.

For example, if a participant's responses are as follows:

- Question 1 (PSS-1): Almost Never (score of 1);
- Question 2 (PSS-2): Very Often (score of 0);
- Question 3 (PSS-3): Sometimes (score of 2);
- Question 4 (PSS-4): Very Often (score of 4).

The total score is calculated as shown below: Total Score = Score of PSS-1 + Score of PSS-2 + Score of PSS-3 + Score of PSS-4 = 1 + 0 + 2 + 4 = 7. According to the categorization, a total score of 7 falls into the Medium Stress category.

Figure 4 shows the distribution among participants. It shows that the medium category, which corresponds to 4–8 scores, has the highest percentage (65%), which was followed by High (24%), Low (7%), and Very High (4%).

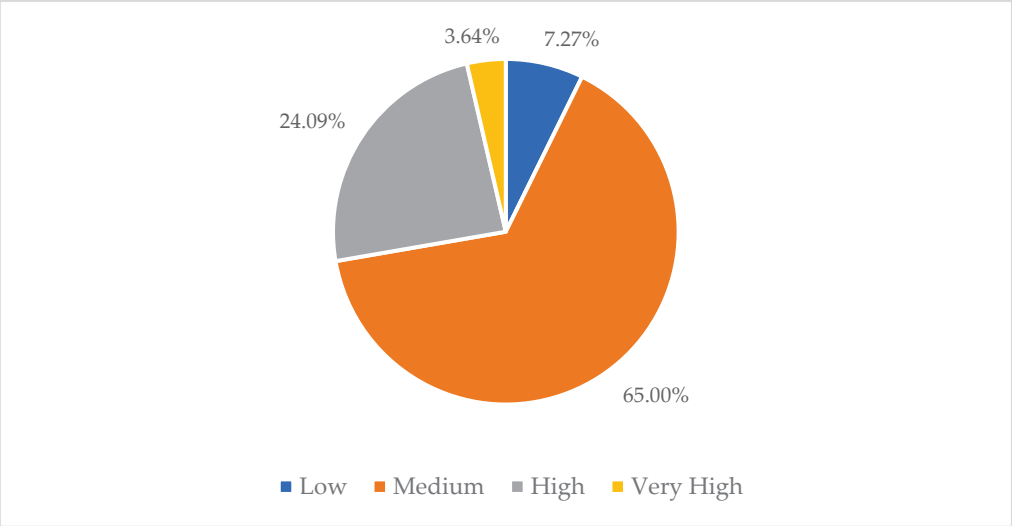


Figure 4. Distribution of level of perceived stress.

3.3. Landscape Values Perception Findings

Original Photographs Versus Manipulated Photographs

According to Table 4, people's preferences to manipulated photographs tended to modify the original attribution given to the photographs slightly. For photographs 1 and 4, the manipulated version translated into lower negative opinions than in the original photographs, whereas in photograph 3, people expressed much more positive opinions, and in photograph 2, negative opinions were actually prevalent.

Table 4. Summary of people's perception and emotions toward the landscape.

Photographs/Adjectives		Anxious/Serene	Restless/Tranquil	Tense/Calm
Photograph 1	Original	Anxious (50.45%)	Restless (35.35%)	Tense (52.73%)
	Manipulated	Anxious (39.09%)	Tranquil (37.73%)	Tense (43.18%)
Photograph 2	Original	Anxious (48.40%)	Restless (45%)	Tense (48.64%)
	Manipulated	Anxious (49.55%)	Restless (49.55%)	Tense (50%)
Photograph 3	Original	Anxious (53.18%)	Restless (31.82%)	Tense (51.82%)
	Manipulated	Serene (45.45%)	Tranquil (56.36%)	Calm (34.55%)
Photograph 4	Original	Anxious (46.82%)	Restless (40.91%)	Tense (45.91%)
	Manipulated	Anxious (35%)	Tranquil (44.55%)	Tense (38.64%)

Green color transparency reflects positive opinions, with dark green having significantly more positive opinions in manipulated photographs than in original photographs and displaying a range of positive opinions from very low (light green color) to very high (dark green color). Finally, the gray color indicates that the manipulated photos have more negative opinions than the original photographs.

3.4. Relationship Between Stress Level and Landscape Values Perception

Multinomial logistic regression determined the relationship between stress level and value perception. Table S1 (Supplementary Material) presents the results of a series of linear regressions examining the differences in the perceived stress levels under different conditions of emotional perception for specific photographs. The photographs are categorized based on the emotional states they evoke: Anxious/Serene, Restless/Tranquil, and Tense/Calm. Comparisons are made across different stress levels (High, Medium, and Very

High) relative to a low-stress baseline. The critical metrics presented for each condition are the estimate, lower and upper bounds of the 95% confidence interval, standard error (SE), Z-score, and *p*-value. Each emotional state category has "Neutral" as a reference level, which means that comparisons are made against this neutral baseline. For example, when studying how Serene, Anxious, Tranquil, Restless, Tense, or Calm perceptions affect stress, these effects are compared to how "Neutral" perceptions influence stress.

Similarly, "Low" stress is the reference category. This means that changes in stress due to emotional perceptions are compared to a low-stress baseline. Each stress level (medium, high, and very high) is evaluated based on how much more or less stress is perceived than the low-stress level.

According to Table S1, for those respondents indicating a High–Low stress level and judging photograph 2 (Anxious/Serene), "Anxious–Neutral" had a significant negative effect (−5.4329, $p = 0.026$). In addition, in photograph 1 (Restless/Tranquil), "Very Tranquil–Neutral" had a very high estimate (22.6392) with a very significant *p*-value (<0.001). Also, in photograph 2 (Tense/Calm), "Very Calm–Neutral" had a very high estimate (−31.1297) with a very significant *p*-value (<0.001).

For the respondents indicating a Medium–Low stress level and judging photograph 1 (Anxious/Serene), "Very Serene–Neutral" had a high estimate (117.9843) with a very significant *p*-value (<0.001). Also, for photograph 2 (Anxious/Serene), there were some positive and negative estimates with a high significant *p*-value ("Anxious–Neutral", "Serene–Neutral", "Very Serene–Neutral"). Also, for photograph 4 (Anxious/Serene), respondents who indicating feeling "Very Anxious–Neutral" had a negative estimate of −8.7050 with a significant *p*-value of 0.027. In a Restless/Tranquil emotional state, for photograph 1, respondents who indicating feeling "Very Tranquil–Neutral" had a positive estimate (222.2857). Also, for photograph 4, respondents who indicating feeling "Very Tranquil–Neutral" had a negative estimate (−7.9392). Also, there were two significant negative estimates in a tense or calm emotional state, which were followed by "Calm–Neutral" in photograph 2 and "Very Tense–Neutral" in photograph 3.

For respondents who reported Very High–Low stress levels, and Anxious/Serene emotional states, for photograph 1, there was a highly significant negative estimate of "Very Serene–Neutral". Also, for photograph 2, there were two negative estimates with a very high significant *p*-value, which were followed by "Serene–Neutral" and "Very Serene–Neutral". For the Restless/Tranquil emotional state, there was a negative estimate (−0.0321) with a very high significant *p*-value for photograph 2 (Very Tranquil–Neutral") and a positive estimate (8.2108) for photograph 1 ("Very Tranquil–Neutral").

4. Discussion

4.1. General Observations

The investigation of visual perception in industrial areas represents a crucial aspect of urban planning and design, and a significant correlation has been observed between this phenomenon and perceived stress. Gaining insight into how individuals perceive and interpret their environment in these areas enables urban planners and designers to make strategic choices aimed at perceived stress reduction and the enhancement of safety. This process involves carefully considering various factors, including the visual aesthetics of industrial zones, the clear visibility of potential hazards, and the general visual effect on the local community.

Several studies [1,6–11,13,14,23] have consistently demonstrated the positive impact of urban green spaces as landscape values on reducing stress levels and promoting overall well-being and explored the restorative effects of green environments on mental health,

emphasizing the significance of landscape characteristics and spatial distribution in influencing stress levels and psychological well-being in urban settings.

Compared to other studies, the present study provided insights into various topics, including perceived stress levels and the emotional impact of photograph manipulation, all of which have important implications in urban planning and management.

The analysis of engagement patterns in perceived stress levels indicates that most participants, accounting for 65% of respondents, fall within the medium stress category, including scores ranging from 4 to 8. Subsequently, a significant proportion of individuals, precisely 24%, encounter high levels of stress. Conversely, a smaller percentage of 7% undergo low-stress levels, while 4% endure extremely elevated stress levels. The distribution of stress levels among respondents emphasizes the high occurrence of moderate stress and emphasizes the significance of comprehending how stress is perceived to provide targeted interventions and support. The fact that most respondents reported medium stress is noteworthy, but its significance is limited by the sample's representativeness. The current data may not accurately represent the study area's overall population. As a result, while the prevalence of medium stress is significant, additional research with a more representative sample is required to validate these findings and ensure broader applicability.

The study's comparison of emotional perceptions in original and manipulated photographs reveals that visual changes significantly impact viewers' emotional perceptions. The effectiveness of these manipulations in altering perceptions of restlessness suggests a complex interaction between visual elements and perceived emotions, emphasizing the importance of visual signals in image processing. For example, photograph 3 is perceived as an anxious place in the original photograph but a serene place in the manipulated photograph.

The linear regression analysis of the impact of emotional perceptions on stress levels reveals significant variations across different emotional states and photographs. While some predictors show statistically significant associations with stress levels, others do not. The emotional perception of manipulated photographs impacts perceived stress levels, particularly serene and tranquil perceptions, which consistently show a decrease in stress. However, the effects vary depending on the individuals' initial stress level. Emotional perceptions significantly impact stress levels with notable variations depending on emotional state and context (photograph).

The most consistent significant predictors are observed in the very serene and very tranquil states, implying that these states can significantly reduce or increase stress levels, depending on the context (photograph).

These findings highlight the intricate interplay between stress perception, environmental appraisal, and individual stress levels, providing insight into the complex dynamics that shape people's emotional responses to their surroundings.

4.2. Implications for Planning

The study's findings have significant implications for urban planning and design, particularly in terms of managing and reducing perceived stress in industrial areas. First, engagement trends highlight the importance of inclusive and adaptable participatory methods that bridge the digital divide and increase community involvement in planning processes. Second, the link between industrial structure visibility and stress emphasizes the importance of strategic landscape design, which includes visual screening, as part of mental health management. Green spaces, for example, significantly improve landscape aesthetics and reduce stress levels, making them critical components of urban and environmental design. While addressing all health impacts, including those caused by petrochemical operations, is critical, incorporating greenery can reduce adverse effects by promoting

mental health and ecological balance. Thus, balancing industrial activities with green space integration benefits both the environment and public health.

This study also emphasizes the link between perceived stress and landscape value perception, urging urban planners and designers to create multifunctional public spaces infused with natural elements. Furthermore, the use of photo manipulation to change emotional perceptions suggests that visual media interventions can boost public well-being and foster positive attitudes toward industrial areas

5. Conclusions

This study evaluates how targeted interventions affect perceived stress and explores the emotional impact of photograph manipulation. It demonstrates that altering photographs can improve emotional responses to industrial settings, suggesting that this approach is a promising tool for enhancing public well-being and perception through visual media. The study also highlights the benefits of integrating participatory methods, such as using manipulated photographs to advocate for community concerns and goals. These images can effectively support public advocacy and mobilize community support by providing visual evidence of potential impacts.

The study faced several limitations that may affect the generalizability and validity of its findings. First, restricted internet access in Iran and low participation from Bagher-Shahr residents, many of whom were undocumented immigrants with limited literacy, limited the sample size and demographic diversity. This highlights the need for more inclusive and adaptable research methods in future studies. Additionally, the reliance on online surveys and a small, demographically limited sample restricts the generalizability of the findings, calling for further exploration of how these results apply to other industrial regions globally.

The study also employed self-reported stress scales, which may introduce subjective bias and affect the validity of the conclusions. Moreover, using a limited set of four photographs and their manipulated versions to represent the landscape around the refinery provided focused insights. However, it could have been expanded with a more extensive set of images to enhance the comprehensiveness of future studies.

Furthermore, the research focused primarily on visual impacts and did not account for other potential stressors, such as odors, which may also influence stress levels and perceptions of the environment. Future studies could incorporate multi-sensory analyses to provide a more comprehensive understanding of the environmental influences on stress.

Finally, the absence of control scenes without the refinery poses another limitation. Including such scenes could have helped isolate the stress associated with the refinery. Without these control scenes, it is difficult to determine whether the observed stress is solely due to the refinery's presence or a broader consequence of living in the vicinity, including factors like fear of the refinery being a target for bombing or other socio-political concerns. This limitation may hinder the ability to fully assess the direct impact of the refinery on residents' mental health and landscape perception.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land14010064/s1. Table S1. Impact of Emotional Perceptions on Stress Levels: A Linear Regression Analysis.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and Approved by the ETHICAL COMMITTEE CONCERNING RESEARCH INTO PEOPLE, SOCIETY AND THE ENVIRONMENT OF THE UNIVERSITAT ROVIRA I VIRGILI (CEIPSA) (CEIPSA-2021-PR-0026, 10 November 2022).

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

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Codesigning More-than-Human Ecosystems with Social and Environmental Systems: The Gamification of NetWall and BioDiveIn

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Abstract: This study explores the integration of gamification into social and environmental systems to enhance urban biodiversity and foster the co-creation of ecosystems. It focuses on two key contributions: the development of tangible ecosystemic interventions, such as habitat extensions and edible landscapes, and the gamification of these interventions to engage communities. The interventions were codesigned using systems-oriented design methods, including gigamapping and prototyping, to produce scalable DIY solutions that empower communities to replicate these practices on their own. Additionally, urban games were created to incentivize participation by rewarding individuals for their contributions to biodiversity restoration.

Keywords: more-than-human codesign; gamification; DIY; systems-oriented design; systemic approach to architectural performance; systemic design

1. Introduction

In 1978, Gregory Bateson posed a thought-provoking question: "What pattern connects the crab to the lobster and the orchid to the primrose and all of them to me? And me to you?" [1]. Inspired by this idea of interconnectedness, this research explores how urban environments can support biodiversity by creating collaborative, multi-species ecosystems. Through practical design interventions and gamified community engagement, this study aims to foster urban biodiversity and enhance ecological resilience. Specifically, this study aims to answer the question: "How can gamified community-driven interventions enhance ecosystem resilience in urban environments through the codesign of more-than-human ecosystems?" This question emerges from the urgent need to address biodiversity loss and fragmented urban ecosystems. Through the literature review of ecosystem resilience and community engagement, we identify gamification as a tool to foster participation and implement practical interventions. This research contributes by co-developing NetWall and BioDiveIn, which are tangible, scalable solutions that aim to reconnect fragmented ecosystems through participatory design. It further examines the role of gamification in incentivizing community action and fostering long-term ecological stewardship.

This project introduces two key ecosystemic interventions—NetWall (see Figure 1) and BioDiveIn (see Figure 2)—designed to provide habitats and edible landscapes for various species. These interventions consist of modular wooden structures installed on the facades of existing buildings, transforming urban surfaces into biodiverse ecosystems.



Figure 1. NetWall Intervention, Stuttgart-Germany (Photo: Behnam 2024).

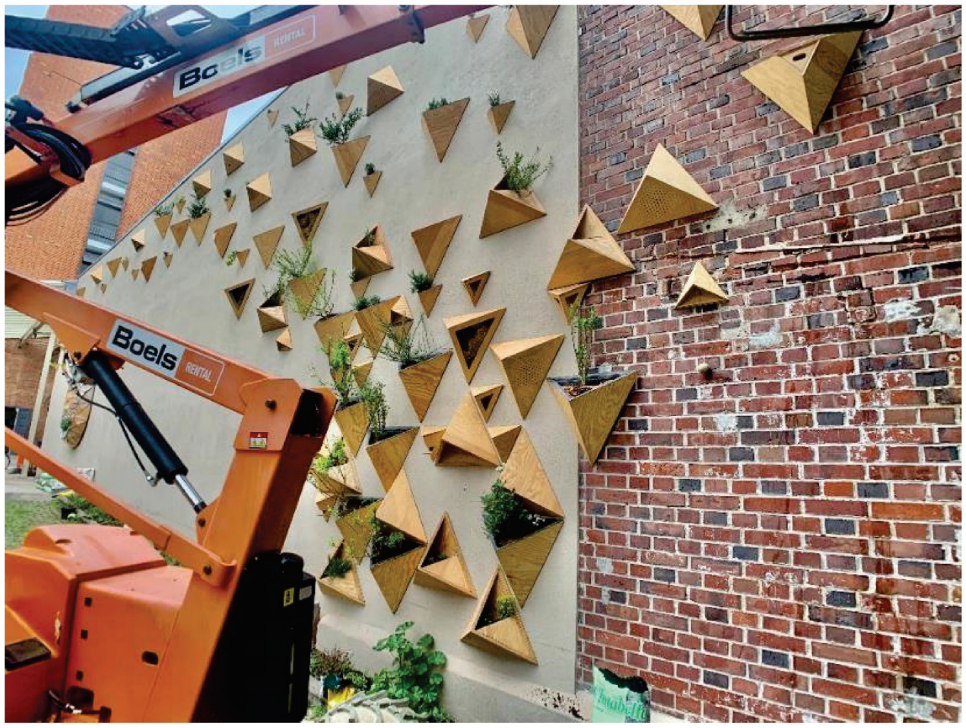


Figure 2. BioDiveIn Intervention, Stuttgart-Germany (Photo: Behnam 2023).

This research stands out due to its focus on strengthening urban connectivity through community-driven DIY engagement. Unlike other DIY initiatives that may emphasize individual participation or isolated ecological benefits, this project integrates systemic design, gamification, and real-life codesign laboratories to create a scalable framework for biodiversity restoration. The modules are tailored to accommodate various species, such as birds, insects, and plants, promoting symbiotic relationships within the urban environment. The interventions leverage simple, scalable DIY methods that individuals and communities can replicate on urban walls, balconies, and other spaces. To encourage widespread adoption, gamification strategies, such as reward systems and interactive urban games, were integrated into the design. These approaches aim to motivate public participation and build ecological awareness, creating a "pattern that connects" humans and other species in urban ecosystems.

The tangible interventions are marked with QR codes, leading to the immersive experience of gamified DIY engagement. The interventions are designed to offer multiple

species habitats and edible and habitable landscapes, with the intention of contributing to a resilient urban ecosystem through symbiotic design [2].

Cities are critical to multiple species' survival. Some of them adapt to life in the cities because they do not find edible and habitable landscapes in agricultural land due to its overtechnicization and increase in pesticides; for some, cities are on their migration paths as they are placed on the rivers [3]. Therefore, our research focuses on urban environments.

Urban biodiversity relies heavily on connectivity between fragmented ecosystems within and beyond city boundaries. These regions include urban centers, peri-urban areas, and adjacent non-urban landscapes that collectively form biodiversity networks. For example, many species require connected corridors to migrate, reproduce, and access food sources, especially as urban areas often intersect with key ecological routes such as river valleys or green belts [4]. Therefore, this project aims to help urban connectivity through the gamification of a DIY network by the local communities as well as the makers' communities.

To generate urban connectivity in the neighborhoods, the top-down way would be too difficult due to the urban density and private property ownership. Therefore, we are motivating the public through series of events and gaming experiences to reproduce our tangible design interventions with edible and habitable landscapes on their own walls and balconies. These, together with the game, serve as the pattern that connects.

This research adopts system interventions as a method for addressing complex ecological challenges, referred to as muddling through the "problematique" [5]. These interventions act as leverage points within broader systems, promoting scalable, ecological, and social change [6]. The currently discussed analogue interventions are the NetWall [7] and the BioDiveIn [8,9], which extend edible and habitable landscapes for multiple species. These interventions also serve as access points, or "touchpoints" [10] for the gamified tools developed in this research, including the urban games GoCOLife [11] and COLife 1 [12] as well as the external citizen science platform Spot-a-Bee [13].

By gamifying biodiversity engagement, these tools create value for ecosystem actors and reward participants for their contributions [14]. The gamified applications motivate human users to DIY recipes while appreciating the value of the ecosystem, while Spot-a-Bee incentivizes participants to document pollinator activity in real-world settings. Looking ahead, the project envisions integrating image recognition technology to quantify and assign value to pollination activities, emphasizing the critical role of bees in urban ecosystems [15].

2. Methodology

This study employs a participatory and iterative design methodology to address urban biodiversity challenges. This research spanned multiple phases between 2023 and early 2024, integrating system-oriented design tools, prototyping, and real-life testing. The timeline of this research aligns with three key design studios under the COLife program: BioDiveIn Intervention (Winter Semester COLife Studio 2023), GoCOLife Game Design (Summer Semester COLife Studio 2023), and NetWall Intervention (Winter Studio 2024). These studios served as collaborative platforms for engaging human and non-human stakeholders, using tools like gigamapping and participatory workshops. The methodology, detailed below, reflects the iterative feedback loop of real-world testing employed in each phase.

The process integrates system-oriented design tools, prototyping, and real-life testing to codesign and implement ecosystemic interventions. Before the more-than-human codesign through the interventions that took place, the interventions were codesigned with human stakeholders, some representing the more-than-human perspective, such as ecologists [16]. This work was developed through design studio teaching, at the Faculty of Architecture and Urbanism, at the University of Stuttgart-Germany.

2.1. Mapping

The codesign process began with collaborative sessions involving human stakeholders, such as ecologists, and systemic design students. The goal was to integrate both human and more-than-human perspectives into the design.

The students first developed minimaps [17], which represented their personal understanding of this project. These maps fostered empathy and collaboration by revealing individual perspectives [18]. The minimaps were then integrated into larger, more comprehensive gigamaps using the Miro platform [19], visualizing complex relationships between ecological, social, and spatial elements. Based on the minimap outcomes, students were assigned responsibilities aligned with their interests and expertise, fostering deeper collaboration and ownership.

For the stakeholders' sessions, the students made the WIP gigamaps as orderly as possible and plotted them on the board. Gigamaps are comprehensive visual tools used in system-oriented design to represent complex relationships between various ecological, social, and spatial factors [20]. They help designers identify connections and dependencies within multi-faceted projects, facilitating collaborative proposals and suggestions.

In this process, the gigamaps were shared with stakeholders, allowing the students to engage with and incorporate feedback into their evolving designs. While Sevaldson, the pioneer of gigamapping, emphasizes the value of messiness in capturing complex systems [17], we suggest that maintaining orderliness during presentations enhances participation and comprehension.

This approach resulted in iterative feedback loops between the messy process maps and the orderly presentation maps. The analogue maps were updated in Miro, oscillating between these two states as part of the codesign process (see Figures 3 and 4). After the interventions were implemented, the gigamaps were finalized. In the case of NetWall, a complex gigamap was also supplemented with a simplified synthesis map for exhibition purposes, facilitating clearer communication. Both interventions—NetWall and BioDiveIn—were accompanied by DIY recipes, which were later gamified in subsequent semesters for broader community engagement (see Figures 5–8).



Figure 3. NetWall gigamapping codesign workshop with stakeholders (Photo: Behnam 2023).



Figure 4. COLife game gigamapping codesign workshops with stakeholders, highlighting the iterative feedback loop process and collaborative design approach (Photo: Behnam 2023–2024).

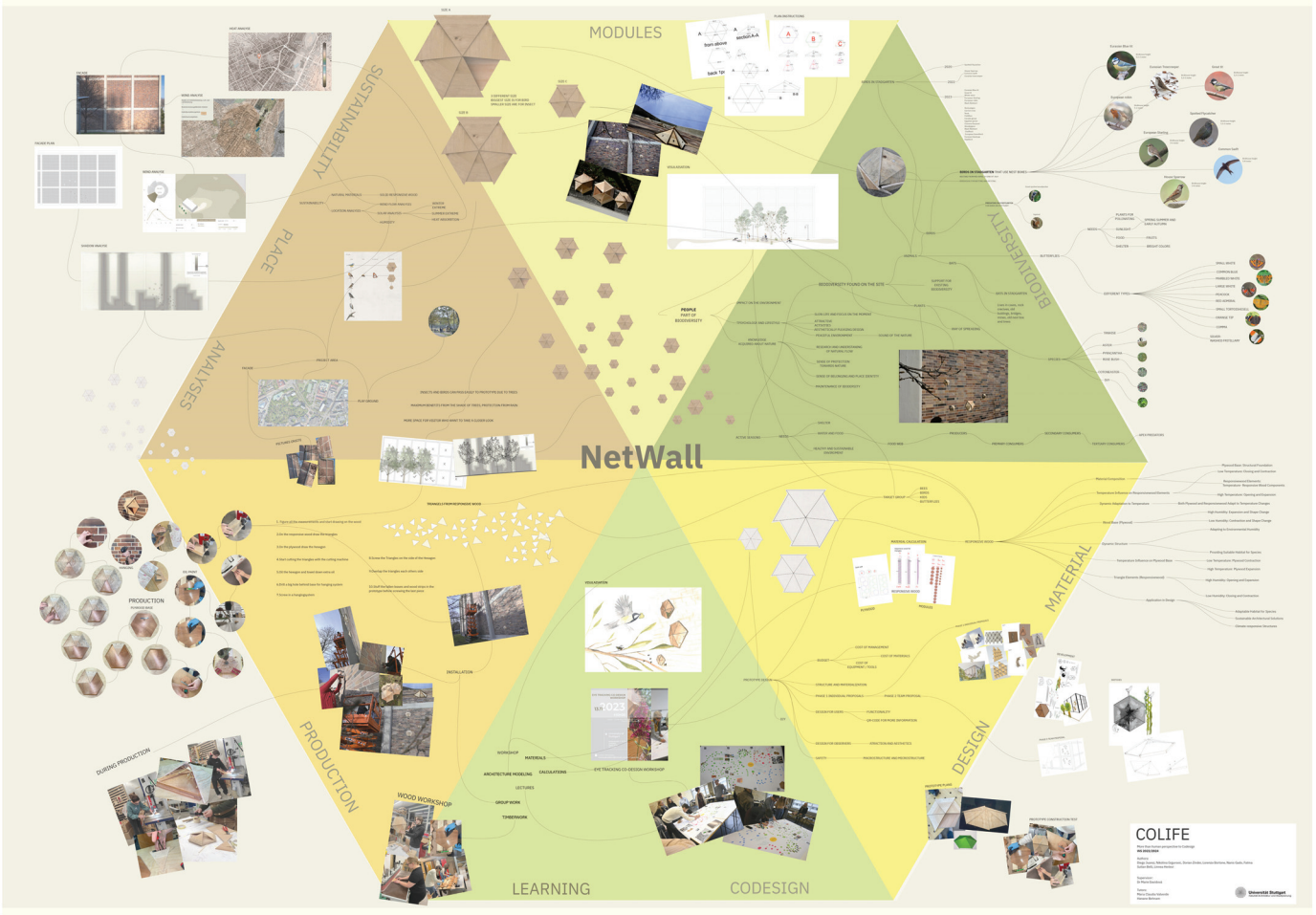


Figure 5. NetWall final gigamap for exhibition purposes (COLife Studio 2024). This image showcases the material and layout of the final gigamap developed for the NetWall intervention, designed for exhibition purposes. For a detailed exploration of the content and connections represented in the gigamap, refer to the dataset: [7] Davidova et al. (2024), COLife_03—Gigamap and DIY (V1 ed.), DaRUS. https://doi.org/10.18419/darus-3986.

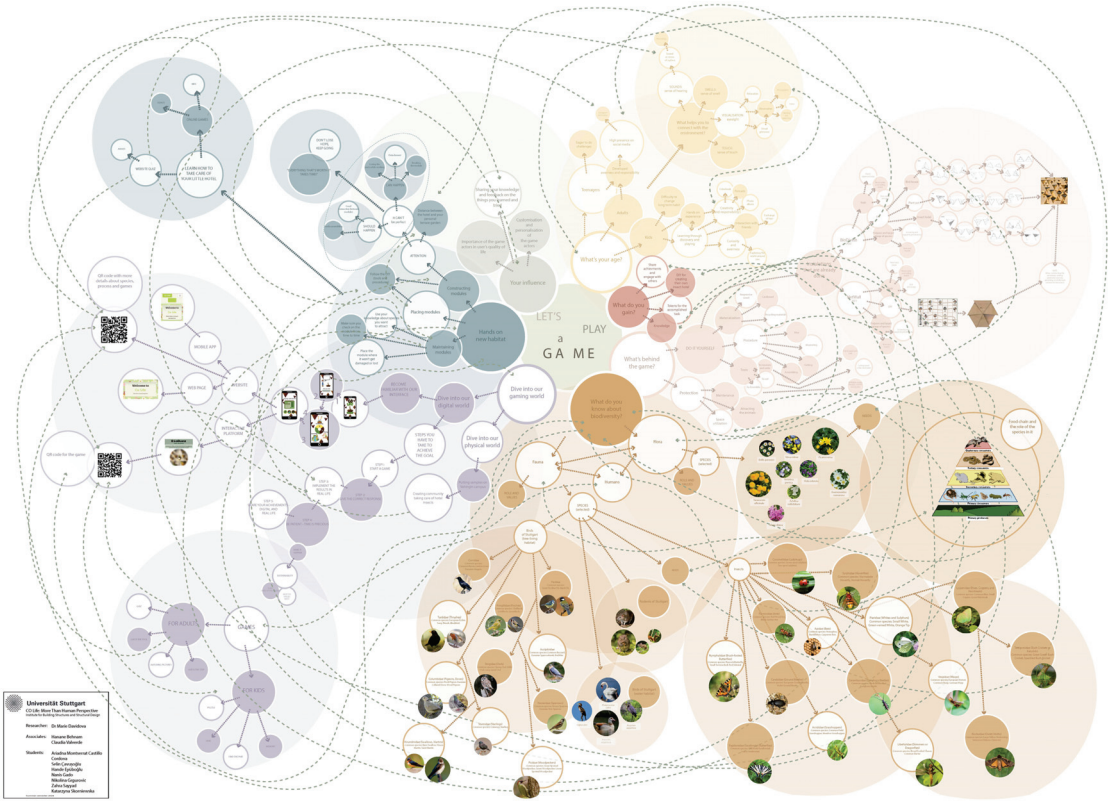


Figure 6. COLife final game gigamap for exhibition purposes (COLife Studio 2024). This figure presents the final gigamap used for the COLife game, illustrating the extent and structure of relationships captured during the design process. For detailed content, refer to the dataset: [12] Davidova et al. (2024), COLife_05: Gigamap and Game Introduction (V1 ed.), DaRUS. https://doi.org/10.18419/darus-4437.

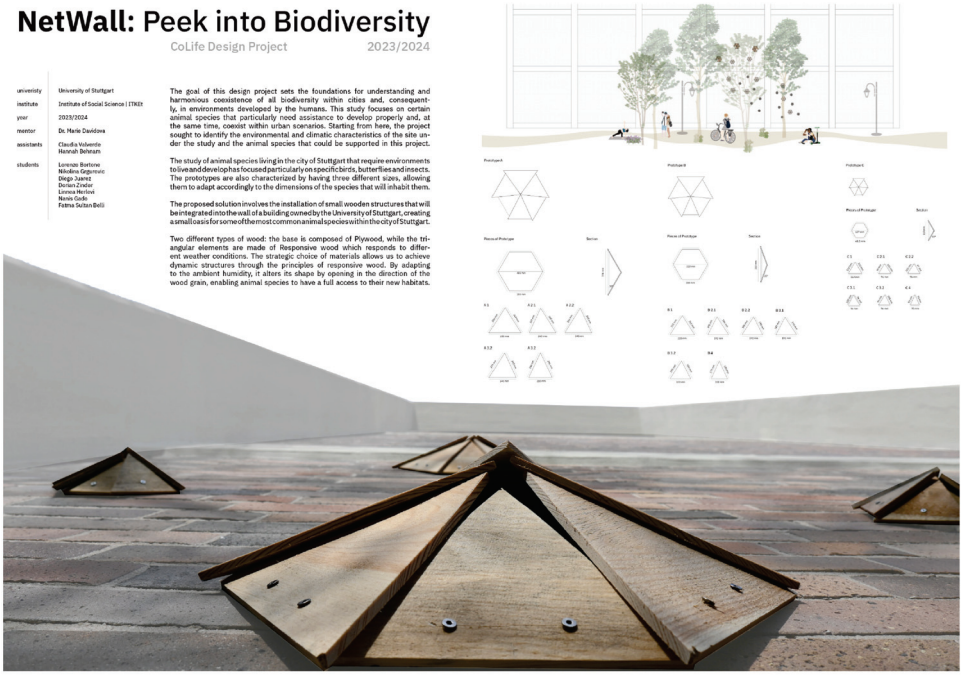


Figure 7. NetWall synthesis map for exhibition purposes (COLife Studio 2024). This synthesis map for the NetWall intervention distills key elements from the gigamap to facilitate understanding during exhibitions. Readers seeking to explore the full map and its detailed content should refer to the dataset: [7] Davidova et al. (2024), COLife_03—Gigamap and DIY (V1 ed.), DaRUS. https://doi.org/10.18419/darus-3986.



Figure 8. NetWall DIY map for reproduction and exhibition purposes (COLife Studio 2024). This DIY map highlights the step-by-step process for reproducing the NetWall intervention, created for exhibition and community use. For a deeper understanding of the underlying content, refer to the dataset: [7] Davidova et al. (2024), COLife_02—Gigamap and Game Design (V1 ed.), DaRUS. https://doi.org/10.18419/darus-3985.

2.2. The Real Life CoDesign Laboratory

The "Real-Life Codesign Laboratory" represents a methodology of integrating codesign practices into real-world settings to test and refine ecosystemic interventions. This approach bridges the gap between conceptual design and practical application by allowing the interventions to interact with their intended environments, users, and ecosystems [21].

2.2.1. Tangible and Non-Tangible Interventions

The tangible interventions, such as NetWall and BioDiveIn, were implemented in urban settings to support local biodiversity. These prototypes were installed on building facades and integrated into real-world ecosystems, enabling interactions with local wildlife, plants, and broader ecological systems. This marked the beginning of the "Real-Life Codesign Laboratory", where real-life codesign really happens.

In addition to these physical installations, the laboratory leveraged non-tangible elements to enhance public engagement and accessibility:

- QR Codes: Embedded on the interventions, the codes provided access to supplementary blogs with detailed information and DIY guides.
- Urban Games: Two gamified tools, GoCOLife and COLife 1, were designed to further engage the public in biodiversity practices [22,23]. These games introduced tasks

such as watering plants and recreating DIY interventions, motivating users to actively participate in urban ecological efforts.

- Citizen Science Application (Spot-a-Bee): Developed by Cardiff University and the University of Glasgow [13], this platform encouraged public participation in ecological monitoring by allowing users to upload images of pollinators. These user-contributed images trained image recognition algorithms to identify and assign value to pollination activities, fostering a new ecology of shared living through technology [24].

2.2.2. Iterative Feedback and Community Engagement

The Real-Life Codesign Laboratory emphasized iterative feedback loops to refine both tangible and non-tangible interventions:

- Ecological Interactions: observations of how local ecosystems interacted with the prototypes, such as which species utilized the modules, informed adjustments to their design and placement.
- Public Engagement: Activities such as ecological checks and community gatherings provided insights into public perceptions and usability. These events also fostered a sense of ownership among participants.
- Technology Integration: tools like Spot-a-Bee and urban games generate data that could inform both ecological research and community engagement strategies.

3. Outcomes

3.1. The Tangible Interventions

The interventions were prototyped along with the gigamapping codesign process, and they are an important part of it throughout the codesign process. They are installed on walls of dense city environments as we need to adapt our cities for biodiversity [3] to offer edible and habitable landscapes. Whilst BioDiveIn intervention uses plywood to generate different modules for various species, user-specific NetWall plays with different sizes of 'responsive solid wood' [25] modules for the opportunistic use of biodiverse species. Design for opportunistic use was discussed by Sevaldson, the father of systems systems-oriented design, who explains that, if you create diversity through a complex design, you reach more opportunities for use, such as a difference between stone and chair—the object to sit on [26]. What showed up in the ecological check, however, is that the user-specific modules were also used by biodiverse species for opportunistic purposes. This is a very important finding, showing that we should not design for specific species as such and rather focus on different opportunities for biodiverse species.

3.1.1. BioDiveIn

The intervention (see Figure 2) is based on several modules, focusing on different bats, squirrels, birds, insects and plants. It is built from local ecological plywood and ecological glue with ecological plastic folia for the plants and pools. The intervention focused on several specific species, extending their edible and habitable landscape. However, whoever was in the neighborhood took the opportunity, which was even better. The intervention involves human participation, such as filling the feeders or water pools for birds and insects. This is achieved through community engagement. However, it generates dependency of the environment instead of being an autopoietic system if we do not include humans as its part, which we do. This intervention was a big success because of its gardening event, where the community planted plants in it for edible landscapes. However, community engagement in such events might also be difficult as engaging the community with no gardening skills led to replanting the pods the year after as the work was not completed

professionally. However, the ecological check this spring showed that multiple species inhabited the intervention. Therefore, it was successful.

3.1.2. NetWall

The intervention (see Figure 1) is based on several sizes of the same module from responsive solid wood. It supports bats, birds, insects, and plants through the surrounding seed bombing of nectarous plants through opportunistic use options. The responsive solid wood works as such: the panels are cut in tangential sections. Therefore, there is a different density on the left and right sides of the panel. This means that, with interaction with relative humidity and temperature, the panels warp [25]. Thus, the single-design cell airs when the relative humidity is low, and there is a high temperature. Also, it closes the cell when it is cold and raining. However, the panels never fully close. Thanks to the fact that the wood from different positions of the tree trunk warps with different intensities, we are generating a climate-diverse environment [27]. This is because each chamber has different panels from different positions of the tree trunk. The better diversity of the climatic environment, the better biodiversity [28]. Generating the opportunities of use through the complexity of the design offers both more intriguing environments as well as multi-species edible and habitable landscapes.

3.2. Gamification of Prototypes

The final phase of this project focused on gamifying the prototypes to engage users in learning about biodiversity and participating in DIY ecological interventions. Two primary gamified experiences were developed: GoCOLife, an interactive game set in an old cemetery, and the CoLife web-based game, which provided educational content and DIY guides for constructing and maintaining bio-interventions. These games were designed to enhance user engagement and promote long-term sustainability of the interventions. The GoCOLife game involved players following clues related to local biodiversity, ultimately leading them to the BioDiveIn interventions where they could scan QR codes to access DIY instructions. The CoLife web-based game provided a more extensive interactive experience, offering multiple chapters and activities that guided users through understanding, constructing, and maintaining urban biodiversity projects (see Figure 9).

The two games were developed in quite different ways. While the first one suggests the payers move within certain locations, fulfilling different tasks until they reach the intervention, the second one is not so spatial and is filled with different quizzes and DIY videos. Both games utilize gamification, which is the application of game-design elements in non-game contexts to boost user engagement, motivation, and behavior change [29]. By integrating features like points, badges, leaderboards, and narrative structures, gamification taps into both intrinsic and extrinsic motivators, effectively enhancing user participation and learning outcomes [30]. In environmental contexts, gamification has been shown to effectively promote sustainable behaviors and increase environmental awareness [31]. Games create immersive and interactive experiences that simplify complex ecological concepts, making them more accessible and engaging for a wide audience [32]. By incorporating challenges, feedback mechanisms, and reward systems, these games encourage users to actively participate in environmental stewardship, fostering long-term behavioral changes [33]. Additionally, digital games offer an opportunity for experiential learning by allowing users to experiment with and observe the consequences of their actions within a simulated environment [34]. This experiential aspect is crucial in environmental education, where understanding the interconnectedness and impact of human actions on ecosystems is vital [35].



Figure 9. GoCOLife game design (COLife Summer 2023 Studio 2023). https://interacty.me/projects/d4d916f6b1a8609b (accessed on 11 January 2025) [11] Davidová, M.; Behnam, H.; Valverde Rojas, M.C.; Guerriero, C.; Yeh, H.; Huang, J.; Köse, M. COL-ife_02—Gigamap and Game Design; University of Stuttgart: Stuttgart, Germany, 2024. https://doi.org/10.18419/darus-3985.

3.2.1. GoCOLife Game

GoCOLife is a location-based mobile game designed to engage users with their immediate urban ecosystems through exploration and hands-on activities. The game requires players to physically navigate urban locations, where they interact with ecological hotspots and biodiversity projects. Missions and quests might include identifying local plant and animal species, participating in habitat restoration, or constructing ecological interventions using DIY recipes. Augmented reality (AR) features further enhance the immersive experience by allowing users to visualize ecological information and potential interventions within their real-world surroundings.

Gamification elements in GoCOLife include a progression system where players earn experience points by completing levels of a questionnaire, unlocking new challenges and content as they advance. The game also features reward mechanisms, granting players access to DIY recipes, tools, and customization options upon the successful completion of activities. Social interaction is encouraged through collaborative play features, such as team missions, community events, and leaderboards, which foster both competition and cooperation among users.

3.2.2. CoLife Web-Based Game

CoLife, on the other hand, is a web-based game that combines gamification with educational content to engage users in enhancing urban biodiversity through interactive learning and DIY project implementation. The game offers a virtual platform where users explore various aspects of urban ecology through modules, quizzes, and instructional content (see Figure 10). The user-friendly interface guides players through step-by-step processes for creating and maintaining ecological interventions, regardless of their prior experience or resources. CoLife's asynchronous engagement model allows users to participate at their own pace, making it accessible to a broad audience.

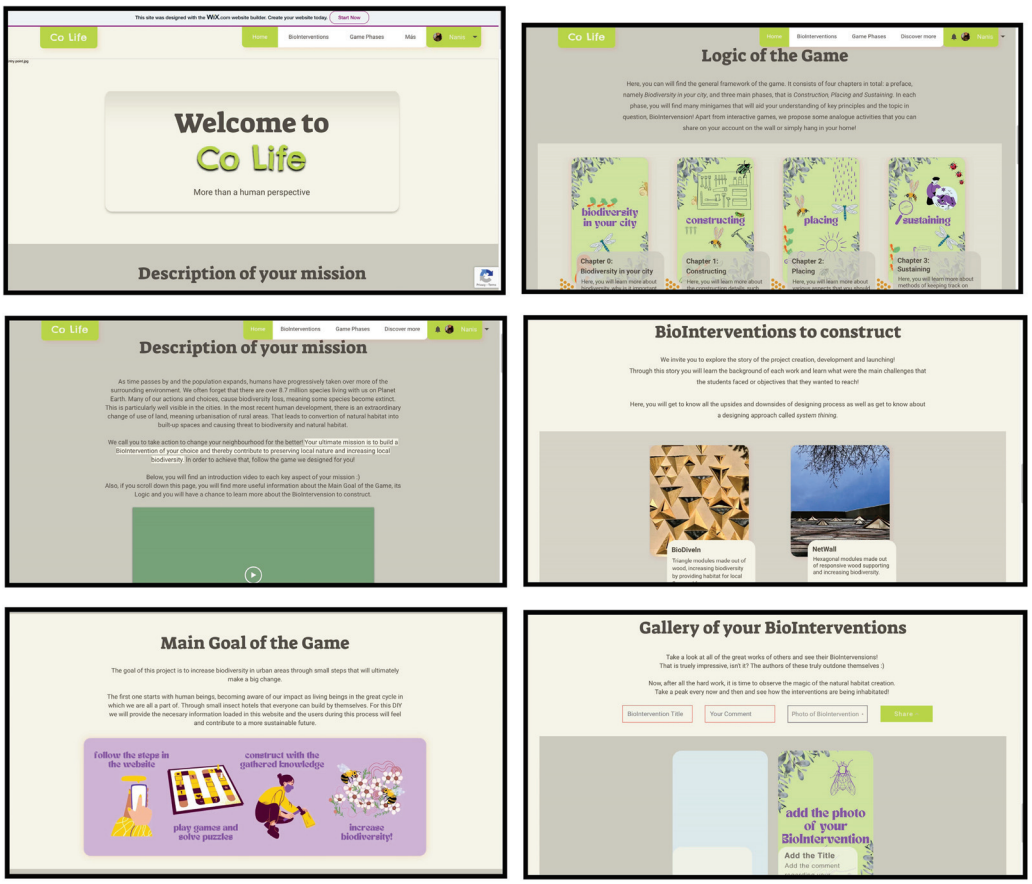


Figure 10. CoLife Web interface structure, retrieved from https://colifebiodiversity.wixsite.com/co-life-1 (accessed on 11 January 2025) (COLife Studio 2024). [12] Davidova, M.; Valverde Rojas, M.C.; Behnam, H.; Montserrat Castillo Cordova, A.; Çavuşoğlu, S.; Eyüboğlu, H.; Gado, N.; Grgurovic, N.; Sayyad, Z.; Skorniewska, K. COLife_05: Gigamap and Game Introduction; University of Stuttgart: Stuttgart, Germany, 2024. https://doi.org/10.18419/darus-4437.

Gamification elements in CoLife include an achievement system where users earn badges and certifications by completing educational modules and DIY projects, highlighting their progress and expertise. The game also features resource management, requiring users to plan and manage materials effectively to complete projects, simulating real-world sustainability considerations. Interactive quizzes challenge users' knowledge of ecological topics, rewarding correct answers with points and unlocking advanced content and DIY recipes. Community sharing is encouraged through in-game forums and social media integration, fostering a sense of community and collaborative learning.

Both GoCOLife and CoLife aim to enhance environmental engagement through their unique design and gamification strategies. GoCOLife immerses users in direct interaction with their local environments, reinforcing knowledge of biodiversity and ecological pro-

cesses through practical applications. It guides users in implementing DIY interventions such as building pollinator habitats and creating water features to support local wildlife. CoLife promotes the concept of a more-than-human economy by illustrating how supporting local biodiversity can improve environmental quality and human wellbeing. It uses its reward system to symbolize reciprocal relationships between humans and non-human actors, demonstrating the mutual benefits of ecological interventions. Through these innovative approaches, both games effectively engage users in environmental education and stewardship, promoting sustainable behaviors and fostering a deeper understanding of our ecosystems.

3.3. Evaluation of Codesigned Interventions

The codesigning process integrated inputs from ecological experts and community stakeholders to ensure the interventions addressed the needs of urban biodiversity while engaging the public in meaningful ways. This participatory approach brought together diverse perspectives, leading to innovative ecosystemic designs, such as NetWall and BioDiveIn, tailored to urban biodiversity challenges.

The iterative nature of the codesign methodology, combined with real-life ecological checks, ensured that both social and environmental systems benefitted from these interventions. These findings highlight the tangible contributions of codesigning to fostering resilient, interconnected urban ecosystems.

3.4. Events

These projects are accompanied by community events, such as gardening and seed bombing (see Figure 11) as well as ecological checks. This serves community engagement as well as finalizes the projects with nectarous plants for the pollinators. These events help to propagate our DIY recipes and our games that are marked with QR codes on our prototypes. For more engagement, we started to cooperate with BUND—Children of the Earth Stuttgart, where we donate our prototypes to their auctions. This way, we are also interacting with a more focused rather than a random audience. Both of these are important. The focused audience can make more impact, and the random audience is from the local community that needs to raise interest.



Figure 11. Seed bombing at NetWall installation opening (Photo: Behnam 2024).

For such community events, we raise the attention of local stakeholders. For example, the local hotel sponsors our receptions, and the local biologist donates information on the ecosystem. The hotel manager is watering our plants as part of his daily exercise for green impact.

4. Discussion and Conclusions

We support real life 'methodological pluralism' in systems-oriented design [36]. This means that we mix several methods and media with a multicentered perspective. Here, the overarching gigamapping, synthesis mapping, DIY recipes, and prototyping are combined with the real life codesign laboratory that engages with the codesign interaction through DIY recipes, citizen science applications, multiple events, and gamification. In our view, it is important that the gigamap is finalized after the intervention to communicate such extensive feedback loops to both the authors and the audience at the University of Stuttgart, exhibited along with the synthesis map and the DIY recipe. It is critical for the understanding of this process codesign tool and the processes and outputs behind it. This navigates the visitors to the real life intervention accompanied with events. The permanent tangible installations serve as a touchpoint [10] for entering services such as QR codes with DIY recipes, gaming applications, and the citizen science application 'Spot-a-Bee' [13]. Therefore, the 'prototypical urban interventions' [37] are generative. They are generative in many senses. One is public engagement in biodiversity support with a more-than-human perspective through gamification. Another one is generating biocorridors across the city as the public DIYs the recipes on their walls and balconies. Larger urban connectivity is crucial for a healthy, biodiverse urban environment, and the same is important public engagement in it [4]. Furthermore, being placed online, these recipes are spreading to makers' communities around the world to be adapted to local ecosystems.

One more important finding is that we should not design for specific species as such and rather focus on different opportunities for biodiverse species.

Theoretically, this case study advances the discourse on community-driven urban ecology by demonstrating how gamified DIY interventions can serve as a leverage point for broader systemic change. It showcases how participatory design can operationalize the concept of "more-than-human" ecosystems, contributing to the fields of systemic design and urban ecology.

Practically, this project offers a replicable model for integrating biodiversity restoration into urban environments. The accessible DIY approach, combined with gamification, empowers communities to build and sustain ecological networks, creating lasting environmental and social impacts. These findings underscore the potential for similar methods to address urban biodiversity challenges worldwide.

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Street Tree Redevelopment in Rome's Historical Landscapes: From Strategic Vision to Streetscape Design

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Abstract: Street trees play a fundamental role in shaping pedestrian sidewalks, squares, and small rest areas, enriching the public space, together with paving, street furniture, and lighting. However, the project of street tree lines along urban sidewalks remains an underestimated issue in urban design and strategic planning, even if it could be a pivotal opportunity for a widespread redevelopment of living streets and public spaces. The present study focuses on landscape aspects of the 'street tree project' intrinsically linked with the identity, perception, and morphological issues of urban spaces, from a strategic vision of the city to the human scale of the urban landscape. In this perspective, we discussed the case of Rome, Italy, where the historical heritage has had an extraordinary value, and where street trees are considered a notable contribution to the landscape identity of the whole city. The administrative council of the Municipality of Rome has initiated a comprehensive census of street trees and is currently developing a Street Tree Masterplan. This plan will serve as a guiding framework, outlining strategies for the conservation of arboreal heritage and the revitalization of the urban tree population along city streets. Based on the empirical evidence stemming from this case study, the discussion highlights the relevance of poorly debated issues, in both the academic and practitioner's literature, mainly concerning the choice of urban trees' species. Choosing the 'right tree species in the right place' has implications that are not only ecological and environmental, but also perceptive and architectural, being intimately associated with the urban scene and the identity of places.

Keywords: landscape design; streetscape; street tree masterplan; public space; urban sidewalks

1. Introduction

Planting trees in cities has several objectives [1–3], among which, air pollution mitigation [4,5], the containment of the 'heat island' effect [6,7], the provision of ecosystem benefits [8,9], biodiversity support [10–12], noise pollution mitigation, and the contribution to the efficiency of the drainage system [13,14] are likely the most relevant in a joint sustainable and resilient vision of metropolitan spaces. Trees provide shade and make rest areas where people can sit more comfortably. They also contribute to the quality of urban space and the well-being of citizens [15–17], with a beneficial impact on people's health [18–20]. Functionally speaking, urban forestry provides nature-based solutions and, when it comes to tree planting along road axes, these solutions can be included in the context of green infrastructures [21–23], both participating in the ecological network of a given city [24–26] and promoting the pedestrian dimension of the route. Trees and vegetation play an essential role in the shaping of public spaces, favoring the socialization and enjoyment of free time outdoors [27–29], whether we consider urban parks or green infrastructure connected to the network of cycle–pedestrian mobility [30–32].

Finally, there is a well-defined aesthetic and ornamental function of trees in urban space [33,34]. Trees and vegetation are essential to creating a quality landscape [35–38], contributing to the design of public space [39] through backdrops, perspective wings, perceptive alignments, and facade masking. Particularly, street trees play a fundamental role in shading pedestrian paths and squares, enriching the public space, together with paving, street furniture, and lighting [40]. In fact, streets of contemporary cities are rapidly evolving, from being simply networks of vehicular traffic to public spaces for people [41], supported by the presence of trees and vegetation [42,43], which make them green infrastructures [44–46], where people can move on foot or by bicycle in a healthier and more vital environment [47,48].

To this end, various initiatives and programs aimed at developing urban forestry interventions [49,50], including the planting of street trees, have been promoted by governments worldwide in recent years.

However, when planning tree lines in a given urban context, a critical question arises: what criteria should guide the selection of the appropriate tree species for a specific location?

Many cities are equipping themselves with specific planning tools for planting and caring for trees in urban environments, including Street Tree Masterplans [51–53] or Urban Green Regulations [54] that, however, often represent practical manuals without an overall vision of the city. In Italy, the Urban and Extra-urban Forestry Plan (approved in 2021) aims to provide a common methodology based on solid scientific references in order to identify and plant 'the right tree in the right place', but it still remains a generic recommendation.

In addition to ensuring the compatibility of the tree species with the biogeographical and ecological characteristics of the site, what other factors must be considered when selecting the appropriate tree for different urban landscapes?

There are several issues concerning the design of street trees on a sidewalk, both when it comes to inserting new trees and replacing specimens along a row. In choosing the right tree for a specific urban street, having its own character, the historical, cultural, and identity factors are first and foremost relevant. Also, tree species are rooted in places and contribute to creating the image of the city.

An additional contingent theme, which is of the greatest importance from the practical point of view of the technical feasibility of the interventions [55], is the one concerning the size of the sidewalks, where there must coexist, as they are vital space for the growth of the trees set in the asphalt and a continuous strip for pedestrians' walking, guaranteeing full accessibility to disabled people [56,57]. On the sidewalk, bars and shops, cycle paths, small rest areas, and spaces equipped with furniture can additionally generate spatial micro-conflicts, while providing diversified opportunities for pedestrians, if they are well organized [58].

From these considerations, it follows that the goal of planting new trees on urban sidewalks should be considered within the broader issue of 'street-scape design', having also important perceptive, historical, and architectural implications.

In this perspective, the present contribution aims to discuss the case of Rome, Italy, where the historical heritage has had an extraordinary value, and where street trees are considered a notable contribution to the landscape identity of the whole city [59]. The administrative council of the Municipality of Rome has initiated a comprehensive census of street trees and is currently developing a Street Tree Masterplan [60]. This plan will serve as a guiding framework, outlining strategies for the conservation of arboreal heritage and the revitalization of the urban tree population along city streets. Through a comprehensive literature review and a visual/narrative analysis of diverse urban contexts within Rome, with a focus on the role of trees, this study documented the critical importance of species

diversity in the design of resilient and sustainable 'streetscapes' within long-established cities possessing significant historical legacies.

2. Materials and Methods

2.1. Study Area

Rome is a city that presents environmental criticalities, associated with pollution and vehicular traffic along the road network [61]. At the same time, it has an important natural capital consisting of the green parks of 'historic villas', protected natural land within the consolidated city boundaries, and vast archeological areas that create an incredibly high 'green landscape porosity' within the urban fabric [62–64]. The green heritage of the Italian capital city extends over a surface area of 400 million square meters, with over 300,000 individual trees, distributed both within green areas and along the roads, for a total of nearly 1200 km of tree rows characterizing the city from a historical, environmental and landscape point of view [65]. Where the historical heritage has extraordinary value, street trees also contribute to the landscape identity, as clearly observed in Rome [66,67]. The current image of tree-lined streets is the result of a historical stratification of different dominant species in the urban scene [68,69].

For instance, *Ulmus* were typical of the Rome of Pope Sixtus V in the 16th century, when the 'olmate' were placed along the routes traveled by pilgrims, who led to the Basilicas. *Plane trees* reflect the desire of the 19th century Italian King Umberto I to give Rome the international character of other European capital cities, using a tree selected as a hybrid in England (*Platanus* × *acerifolia*). The *Cupressus sempervirens* of the archeological walks, the domestic pines (*Pinus pinea*), and the holm oaks (*Quecus ilex*) of a central district surrounding the Vatican City such as Prati, Western Rome, have contributed to creating that image of the Roman landscape of the twentieth century. These were promoted, over time, in the well-known design projects of a major architect and landscaper of that time, namely Raffaele De Vico. Trees in Rome are clearly an expression of historical periods and are diversified in the different urban neighborhoods.

Designing street trees in Rome means, from the point of view of urban and landscape design, dealing with the urban form of the eternal city, which is given by the road layouts, the morphology of the different settlements [70], and its architectural, archeological, historical, and naturalistic emergencies. We should consider, together, the porous structure of the urban fabric, into which the historical parks, protected natural belts, and archeological areas are inserted, including the general topography, with the course of the Tiber and Aniene rivers, the historical 'Ancient Roman' walls, and other consolidated elements in the urban scene, which create margins, backdrops, alignments, spatial conformations, and perceptive relationships.

The morphological structure of Rome is characterized by the radial progression of consular roads, from the central districts towards the periphery. Over time, the consular roads have become aggregating filaments of the built fabric, which extended beyond the metropolitan region, exerting traffic congestion. On the other hand, these roads cross different landscapes, namely in peri-urban territories where, despite environmental fragmentation, fragments of widespread naturalness coexist with areas where the relict (rural) landscapes are still recognizable. These are territories where local biodiversity is well preserved, composing a complex matrix of widespread natural, historical, and archeological heritage.

2.2. Study Objectives

The structure of the article is reported as follows. After introducing a reference scenario, Section 2 analyses the case of Rome, Italy, where a census of street trees is currently

being carried out using Geographic Information Systems supporting the masterplan of street trees, designing future strategies for the expansion of tree cover and for the care of the existing tree heritage.

Rome is a particular city, for the richness of its historical and identity values, for the enriched stock of tree biodiversity [71,72], as well as for the complexity of social functions [73] and economic activities that coexist in the urban scene.

Starting from the case study, we propose a series of reflections on the practical issue of new street-line tree design. In particular, we discussed some possible criteria for choosing street trees' species based on the landscape performance of trees by type of street, grounding the debate both on an architectonical and ecological discourse. The case of Rome, with all its historical implications, should exemplify the intrinsic complexity of planning and designing street tree lines in other cities with the same characteristics in terms of cultural heritage.

Finally, we debate the role of native species as making up the current street tree lines; they are often under the attack of pathogens, but they usually appear more natural and are well suited to the present landscape context. We also discuss an alternative use of an alien plant species assumed to be more resistant to climate change.

3. Results

3.1. The Planning Strategy of the Street Tree Masterplan of Rome Municipality

Starting from a systematic census of street trees and an interpretative framework, which classified streets based on the landscape performance of the tree rows, the masterplan proposes specific strategies in terms of the replacement and development of new plantations [60]. From a methodological point of view, a classification of trees by dendrological types and streets based on the required landscape performance was carried out according to a hierarchical scheme with four types of streets: (R01) green infrastructure, (R02) ecological corridors, (R03) 15 min urban axes, and (R04) neighborhood residential streets. Appropriate intervention strategies were formulated for the different types of streets, including the identification of the types of trees and the simulation of possible transformation scenarios. A brief description is provided below.

'Green infrastructure' roads (R01) are 'consular' roads intended as infrastructural axes (radial) of ecological connection between the large internal urban green areas and the open territory (Figure 1). The trees planted on consular roads are essentially *Pinus pinea* and *Platanus* × *acerifolia*, with a few exceptions. They are trees that have a role as territorial landmarks. The proposed strategy for these types of roads emphasizes the reinforcement of existing linear tree plantations while respecting the role and identity of the existing trees. By increasing tree density along radial roads, the plan aims to facilitate the reconstruction of green wedges that penetrate the urban areas, thereby reconnecting the surrounding countryside metropolitan greening.

R02 roads, characterized by wide sections designed to accommodate high-speed traffic, possess the potential to function as a foundation for an internal, tree-lined ecological network. This network would effectively interconnect a vast urban green mesh. Furthermore, these roads play a strategic role in establishing a linear hub for sustainable mobility and associated infrastructure.



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

Figure 1. Selected examples of radial ('consular') roads in Rome, classified by the masterplan as 'R01—green infrastructure'; (**a**) Cristoforo Colombo Street, with *Pinus pinea* that constitutes an identifying landmark; (**b**) Nomentana street, characterized by a quadruple row of *Platanus* × *acerifolia*.

The selection of tree species will prioritize high-quality specimens with expansive canopies. Furthermore, a diverse range of species will be incorporated to enhance biodiversity and strengthen ecological corridors within the urban environment.

R03 role streets (urban axes of the 15 min city) are the main axis within various districts, characterized by built-up frontages and ground-floor commercial establishments. They function as pedestrian-oriented streets where trees provide shade for pedestrians and contribute to the overall aesthetic appeal of the urban landscape (Figure 2). For this type of road, smaller species are suggested, even with seasonal blooms, which can contribute to improving the quality of the public space, providing shade on the sidewalk and making the seating areas more comfortable.



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

Figure 2. Three-dimensional simulations with planting of new trees on R03 type roads (15 min axis) in Rome; (**a**) Cola di Rienzo Street, (**b**) Marconi Road, both in Central Rome. (Source: author's elaboration, 2024).

Planning strategies for existing trees and new plantations in Rome are grafted into a coherent framework of interventions on public greenery, respecting local identities and the urban context. In a figurative and symbolic interpretation that has sometimes been given to the urban form of the city, the consular roads are the rays of a star, delimited by the circumference of the ring road, with a longer strip of territory, which extends toward the Tyrrhenian Sea coast. With respect to its urban form, the future vision of the city is that of a "green star" (Figure 3), increasingly green, where street trees reinforce the morphological structure of the city and its identity.

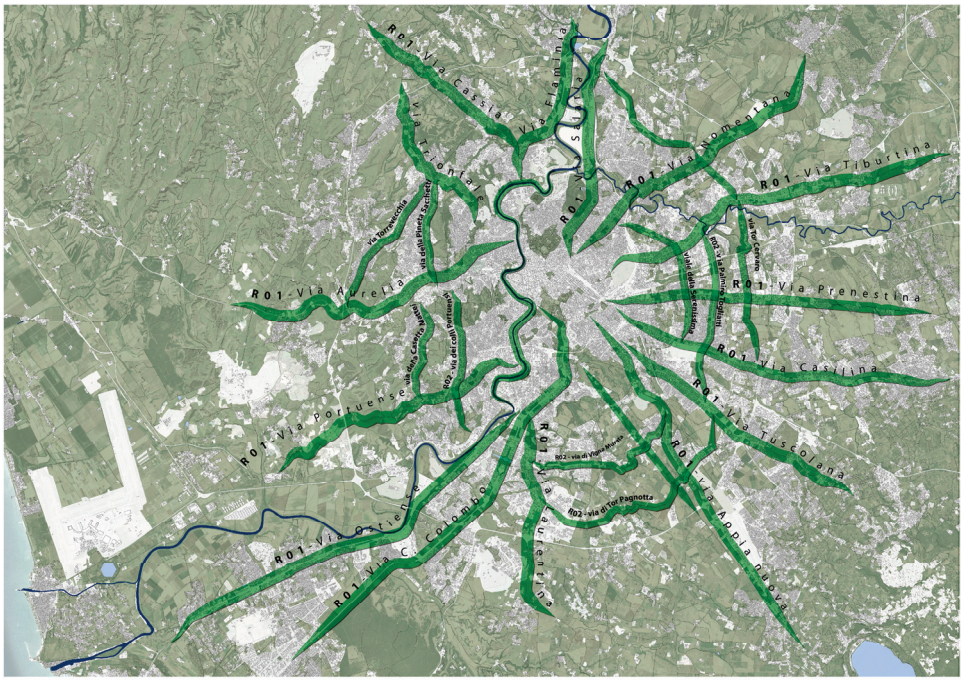


Figure 3. The morphology of Rome can be envisioned as a 'green star', where street trees enhance the city's settlement form. Conceptual drawing highlights the radial roads (R01) connecting the countryside to the city. (Source: author's elaboration, together with arch. Marco Degaetano, 2023).

3.2. From the Strategic Vision to the Human Scale of Streetscape Design

When we move from the urban and strategic dimension of the Plan to the scale of the sidewalk, a series of landscape and perceptive assessments come into play, which the project should take into account.

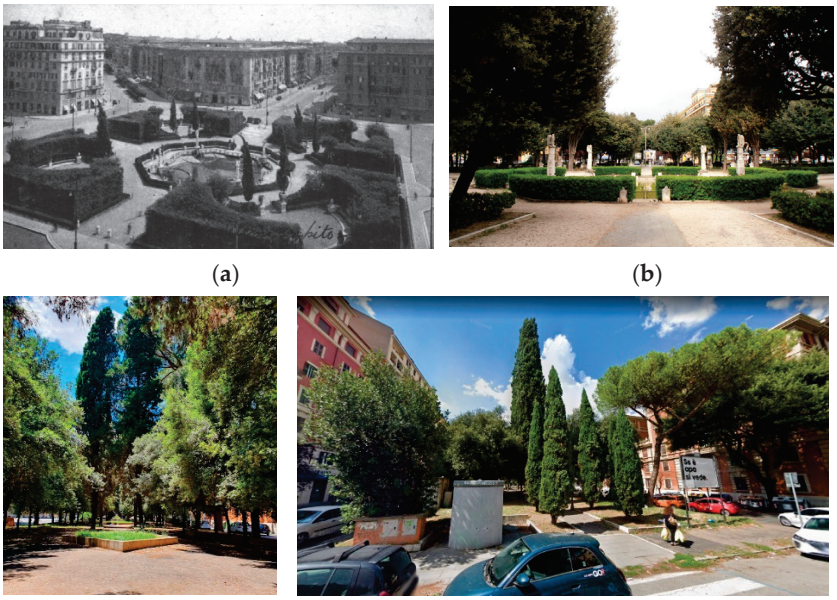
On the scale of the street project, the replacement of old trees and new tree plantings gives the opportunity to work on the redevelopment of the public space [74–76], in synergy with any other project remodeling the road section, e.g., allowing the introduction of cycling paths, with the creation of small rest areas and the provision of street furniture.

Coming back to the case study of Rome, the local administration is tackling a series of interventions for the redevelopment of the public space also on historic roads, with the aim of planting new trees, removing stumps, and replacing trees that have reached the end of their life cycle for pathological reasons. The following images show examples of some practical interventions reflecting the historical and architectural implications underlying the choices of planting new trees in a given location.

For instance, work is being carried out on Raffaele De Vico's project for the historic fountain in Piazza Mazzini and on the linear park on Viale Mazzini (Figure 4), which looks like a grove of holm oaks, with access steps marked by cypress trees (Figure 5). The linear park designed by De Vico appears diversified and complex from a perceptive point of view, with an assortment of tree species, which provides dimensional and chromatic variables. Rome Municipality is also studying a project for the redevelopment of Piazzale Clodio (Figures 6 and 7), which represents the head of the linear park, currently occupied by two asphalt flowerbeds used as a car park. The idea from the local administration is to de-pave the traffic islands, transforming them into green tree-lined flowerbeds.



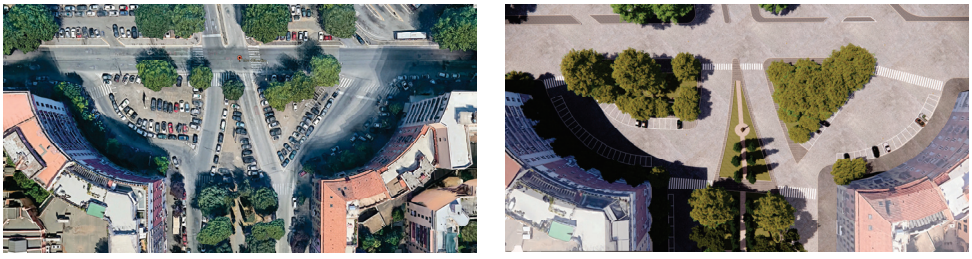
Figure 4. Orthophotos and landscape photos of Mazzini Avenue in Central Rome; images taken from Google Maps and the author's archive.



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

(**c**) (**d**)

Figure 5. The Garden Fountain of Mazzini square, designed by Raffaele De Vico. (**a**) A historical image of the Plaza; (**b**) image of the Plaza in 2024; (**c**) the linear park of Mazzini Avenue, with a grove of *Quercus ilex* and the access passages marked by *Cupressus sempervirens* (**d**).



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

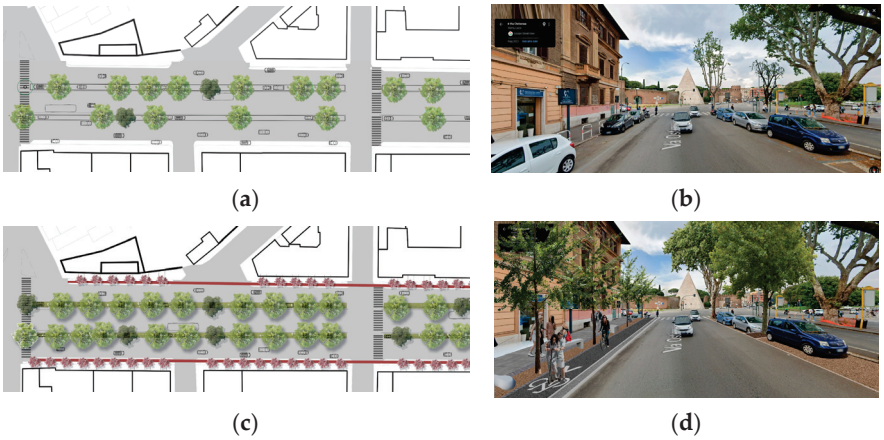
Figure 6. Project simulation for Piazzale Clodio: (**a**) Aerial view of the current situation, showing flowerbeds used as parking spaces; (**b**) proposed scenario featuring the removal of pavement from the flowerbeds and their transformation into green spaces.



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

Figure 7. Proposed scenario for the entrance to the linear park from Piazzale Clodio: (**a**) Current situation featuring a flowerbed covered with asphalt; (**b**) proposed design for the new gateway to the linear park, including two rows of *Cupressus sempervirens*.

Another example is Via Ostiense (Figure 8), a consular road, which features two central medians with an alternating arrangement of plane trees and holm oaks, as well as two relatively narrow lateral sidewalks. The project must balance two somewhat conflicting objectives: developing a bike lane on both sides of the lateral sidewalks and restoring the street trees that have been lost over time.



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

(**c**) (**d**)

Figure 8. Ostiense Street, Rome: (**a**,**b**) Existing conditions with two central rows on the central medians alternating plane trees and oak trees, most of which have been lost; (**c**,**d**) project simulation showing new tree plantings in the central medians (*Platanus* × *acerifolia* and *Quercus ilex*), along with the redevelopment of the lateral sidewalks featuring a new row of *Cercis siliquastrum* and a cycle path on both sides. (source: author's elaboration, 2024).

4. Discussion

This case study on Rome's tree lines reflects the complexity of planting new street trees, which cannot be relegated to the mere management of the existing trees by Municipal Offices. On the one hand, a strategic vision of the entire city is needed, which guides choices on the replacement and new planting of trees along urban streets. In this sense, the interventions of the replacement and planting of new street trees should be defined according to the urban role played by the road and the trees themselves, fitting into a coherent reference framework, taking into account urban forms and the identity of metropolitan landscapes.

At the same time, it should be considered that what is indicated in the strategic framework of the masterplan represents a general guideline, which requires an in-depth analysis in the executive phase and assessments to be carried out on a case-by-case basis.

Trees play an important role from a landscape and perceptive point of view [77,78], placing themselves in relation to the road section, the pedestrian path of the sidewalk, and the urban fronts of the facades.

From a landscape point of view, it is also important to evaluate morphological and perceptive factors, in terms of the relationship between tree rows and the urban scene. The shape of the crown, the bearing of the trees, the strength, the color of the foliage, and the seasonality of any blooms, have an important perceptive value in the urban context, characterized by the morphology of the building fabrics, the figurative characteristics of the urban fronts, edges, limits, and openings towards open spaces.

A peculiar aspect of planting trees along the streets (i.e., replacement within a tree row or creation of a new street tree) is the choice of the species to be used in the different interventions, which should take into account the indications of both general and specific nature [79,80]. The first aspect is the origin of the species [81,82]. The National Strategy for Urban Greenery highlights the importance of selecting native plant species consistent with soil quality and the ecological characteristics of the territory [83–85], in order to ensure the extended functionality of the ecosystem benefits. In cities, and particularly for the creation of street trees, exotic species have been used to a large extent. A study carried out by the Italian Botanical Society (2019) on 15 Italian cities (including Rome), documented how more than 50% of the species used in tree-lined avenues are exotic. This study proposed to define the species to be included in street trees based on the so-called 'potential' vegetation (based on the well-known ecological notion of 'vegetation series') and to plan the replacement of the trees taking into account the phytosanitary and stability problems of each species.

According to Ferrini [86], it is important to contextualize the type of intervention to be used, since the most effective strategy to improve urban biodiversity is 'differentiation' rather than 'simplification' [87,88]. A management strategy for the replacement of old and/or dangerous rows or plants, particularly those that contribute to the distinctive character of specific areas within the city, should prioritize a phased renewal approach. This strategy aims to ensure the visual continuity of tree-lined streets over time [89]. In cases where there are no native species suitable for a particular context and where the non-invasiveness of a given species is ascertained, it is possible, sometimes even desirable in relation to the effects of climate change, to plant exotic species.

Regarding species selection, a decision-making process is established that prioritizes the preservation of existing tree species within the socio-economic context. This approach emphasizes the protection of pre-existing species within the tree stand, particularly when replacing missing trees. Conversely, in the case of renewal of the entire row (e.g., because of old age or unsuitability of the pre-existing species) or the creation of a new street tree stand, it is appropriate to deal with the need to favor local (native) species compatibly with the limitations imposed by climate change forecasts. The more consistent use of autochthonous species according to the local flora [90], however, is confronted with the availability of suitable material from a nursery perspective. In relation to climate change, it appears important to encourage the use of local origins (in the case of Rome, using forest propagation material collected at least in the central Tyrrhenian ecological region). However, at present, the nursery system is not always able to ensure this need, with the risk that the demand for autochthonous species is satisfied only with the supply of non-local material (e.g., a field maple produced from seeds collected in Northern France, or a holm oak from Northern Spain, or origins of geographical and climatic contexts completely different from those of Central Italy).

After all, even the 'choice of the right tree in the right place' is not at all automatic, moving between contrasting assessments. The criterion of the historical identity of tree species linked to places will have to deal with the need for species diversification, in terms

of resilience and biodiversity. While the criterion of utilizing native species remains crucial, it must increasingly incorporate the long-term need to introduce species that exhibit greater resilience to the impacts of climate change.

A choice of tree species, therefore, which may be valid from an ecological point of view, because it is more adaptable to climate change, may not be a good choice from a landscape and perceptive point of view. Can it be legitimate to replace the plane trees (*Platanus* × *acerifolia*) along a historic street in Rome, attacked by a pathogen, with *Pyrus calleryana* 'Chanticleer', which is proving to be more resistant to attacks? Can we replace the pine trees along the consular roads, which cause problems to the road surface with their roots, which have now taken on an important role in designing the image of the city? One might also ask whether it is nicer to see a row of trees all of the same species and size, or a more articulated rhythm of different trees in an urban context. These are questions that cannot be answered without a long, interdisciplinary discussion of their positive and negative implications.

It is always within the scope of the intervention project that specific assessments should be made by the designer, who must take into account together of different aspects, dealing with the ecological, environmental, architectural, historical, cultural, and identity nature of urban landscapes.

On the scale of the sidewalk project, moreover, the design of the tree rows along the street pavement remains a complex issue [91], which presents conflicting situations and overlapping elements in a limited space, including trees, in the limited space of the sidewalk, where a variety of users coexist. The conflicts that can arise from the unsustainable or inappropriate planting of trees on the sidewalk essentially concern the following: (i) the transverse dimension of the sidewalk; (ii) broken tiles and exposed roots; (iii) interference with underground utilities; and (iv) interference with different activities and functions that occupy public space.

On the other hand, planting trees and maintaining existing trees along urban sidewalks, could be a great opportunity for a widespread and capillary redevelopment of the urban public space [92,93]. The sidewalk is like a continuous line that moves within the urban space, providing the opportunity for pedestrians to reach different points of the city and to access different functions that pertain to the public space. In a compact city, where the urban fronts rest on sidewalks, and the ground floor of the buildings is largely used for commercial activities, trees provide shade and encourage the flow of pedestrians walking, favoring environmental comfort and urban sociality [94]. In the streets of great inter-neighborhood connection, where the road section allows it, trees and vegetation act as a green infrastructure [95,96] or as an ecological corridor for biodiversity, but also as a support structure for slow mobility. The growth site of trees and vegetation can increase the drainage surface of the sidewalk, generating intrinsic benefits on the ability to intercept rainwater flows, a particularly relevant matter from a climate change perspective. The redevelopment of street trees, with the implementation of new plants is, finally, a strengthening element of the quality of the pedestrian sidewalk and the public space in general [97,98].

5. Conclusions

The street tree redevelopment project of Rome, compared to the Street Tree Masterplan of other cities in the world, discounts the complexity and relevance of the city's history, with a projection towards the future, which should duly take into account its consolidated identity. The Rome Street Tree Masterplan must prioritize the maintenance and care of existing trees, with a strong emphasis on individual plant health. Recognizing that the preservation of this arboreal heritage constitutes the core objective, the plan should

incorporate a comprehensive approach to tree care. The assumptions underlying a specific street tree planning tool are multiple and have been summarized in this study, representing a concrete example for other European cities that could also be adapted to contexts with similar surrounding environments. Planting trees on the sidewalks along the streets therefore represents not only an important tool for the implementation and conservation of the tree heritage at an urban and metropolitan level, but also an opportunity to improve the quality of public space, and the quality of life of citizens.

Intervening on the network of street trees can be an important opportunity for cities that are facing the global challenges of climate change, both to strengthen green infrastructure, counteract the heat island, and ensure a widespread redevelopment of street pavements. When considering the effect on people, the street tree project should take into account a range of contingent and interfering issues related to the road surface. At the same time, it should seize opportunities to work on the redevelopment of public space, in synergy with projects aimed at remodeling the road section, including the introduction of cycle paths, widening of pavements and the provision of street furniture. European cities, by virtue of their existing heritage of trees and green spaces, should become more aware of the strategic value of street tree redevelopment in streetscape design.

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Recognising the Fourth Nature: A Case Study of Spontaneous Urban Vegetation in Southwest Australian Cities

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Abstract: Urban nature exists in all cities, including spontaneous nature. Spontaneous vegetation has been well-documented in the broader ecological literature in the Northern Hemisphere in recent decades. However, the recognition of, and interest in, spontaneous nature in Australia is limited. Our study initiated research on spontaneous vegetation in Southwest Australia from a landscape architectural site analysis approach with vegetation surveys. This study created an inventory of plants in four biotope types (specific abiotic environments with associated plant communities), i.e., cracks, walls, margins, and vacant lots, in two cities. Twenty-four sites were surveyed four times over a calendar year, and 145 plant species were identified. More than 90% of the species were naturalised, with native ranges most common in the Mediterranean Basin (34 species), and predominantly annuals (73 species). Only eight species were native to Southwest Australia. Our analysis revealed some of the cultural and ecological characteristics of these sites and species, i.e., environmental histories, pollinator habitats, the temporary statuses of sites with spontaneous nature, and their potential, e.g., altering maintenance schedules to retain foraging resources. Therefore, this study recommends further exploration of spontaneous nature through small-scale site analysis approaches and at larger scales for a more detailed understanding of this, at present, overlooked part of nature in Southwest Australian cities.

Keywords: spontaneous urban nature; spontaneous vegetation; urban biotopes; non-native species; four natures approach; design-based research; Southwest Australia

1. Introduction

Human cultures forge cities and their built environments. Cities are highly manipulated landscapes continually disturbed by anthropogenic forces but nonetheless include nature. Nature in cities, or urban nature, exists in a variety of intentional and unintentional (spontaneous) forms, or 'natures', unique to the built environment and encompasses all plants and non-human animals that live and dwell in cities [1]. Discussions, interpretations, and definitions of urban nature vary widely across disciplines [2]. The current study was conducted from the perspective of the 'Four Natures Approach' proposed by German urban ecologist Ingo Kowarik [3].

The 'Four Natures Approach' [3] is intended to simplify diverse cultural interpretations of urban nature into four typologies and emphasise their characteristics from a qualitative perspective so the general community can acknowledge, identify, and understand different types of urban nature on their own merits in planning and decision-making processes. In brief, the four typologies are natures of the first, second, third, and fourth kinds. The 'first' refers to landscapes and ecosystem remnants representing preindustrial or pre-colonial natures such as old-growth forests. The 'second' refers to landscapes and

ecosystems of modern agriculture and forestry practices, such as crop fields. The 'third' refers to designed and horticultural landscapes with high cultural agency and constant maintenance, such as parks and gardens. The 'fourth' refers to a spontaneously growing nature, independent of design or planning, such as plants in pavement cracks and walls or on vacant lots.

While not generally perceived as the most attractive area of enquiry, the fourth nature, spontaneous nature, exists in all cities [4], though its cultural and ecological characteristics have been well-documented most prominently in Germany, the United Kingdom, the United States, and Japan [5]. Spontaneous urban vegetation in these locations has displayed unique cosmopolitan plant communities specific to places [6,7], with links to cultural histories such as previous land use [3]; ecological characteristics such as site suitability, erosion control, and excess nutrient uptake [8]; and habitat provisions such as increased nectar resources for pollinators [9].

At present, the recognition of, and interest in, the fourth nature in Australia is limited and, therefore, it is not well-understood. A systematic review of articles published about spontaneous natures by Rupprecht et al. in 2015 [5] (termed 'informal green spaces' to encompass the array of different terminologies used in the broader literature) found 174 papers published in English, German, and Japanese, with a marked increase in publications from the year 2000. Of these publications, only four were in Australia, and none focused on vegetation. More recently, two articles published by Stanford et al. [10,11] have focused on governing and mapping informal green spaces in Melbourne using a socio-ecological framework. These studies explore the potential of these spaces to contribute to the number of accessible green spaces available for urban residents, as habitats for urban pollinators and fauna, and as connections between other green spaces within the urban landscape. These two studies may be the start of a more holistic perspective in the study of spontaneous urban nature in Australia. To date, there have been no published studies with a focus on the fourth nature in Western Australia.

There are several reasons for the lack of interest in spontaneous urban nature in Western Australia. One prominent reason is that the Southwest Australian Floristic Region (SWAFR) in Western Australia is a global biodiversity hotspot with over 7000 native vascular plant species, at least 2500 of which are of conservation concern [12]. This attribute emphasises the uniqueness of native plants and landscapes of the region and, crucially, the risk of losing them. Less than 10% of the pre-colonial landscape of SWAFR remains intact [13] due to land clearing and urban development from around the 1830s onwards. The SWAFR has been unglaciated since the Permian Period (298.9–251.9 million years ago) [12], and most native plant species that grow in this region have evolved to live in 'old, climatically buffered, infertile' landscapes [14]. This means that they rarely re-establish amid the ongoing disturbances encountered in urban landscapes (e.g., clearance of native vegetation and soils for housing construction). In addition, there are now more than 27,000 introduced plant species in Australia, with over 10% of them considered naturalised in the 'natural' environment and many considered a financial nuisance in agricultural landscapes [15].

This means that, first, most plant species growing spontaneously in Southwest Australian cities are not native. And second, previous ecological research involving urban nature in the region has focused on the conservation of remnant nature (nature of the first kind) or native revegetation [14,16,17]. It is understandable why urban biotopes with spontaneous vegetation have been overlooked thus far. However, because the built environments of Southwest Australia displaced many pre-colonial landscapes and ecosystems, an understanding of urban nature solely focused on a retrospective or prospective view of the first nature with an acceptance of the designed or horticultural spaces of the third

nature provides an incomplete picture [2]. In order to understand the urban nature in the cities in Southwest Australia from a holistic perspective, spontaneous nature needs to be recognised and its cultural and ecological characteristics considered.

Landscape architects work predominantly in urban landscapes and the third (designed and horticultural) nature; however, the scope of landscape architecture is broad and its scale large. Wherever a design project falls within this scope, and whatever design principles are used, the common and crucial element is understanding a site and its context to create a suitable design. In their introductory text to landscape architecture, Holden and Liversedge claim that "landscape architecture is nothing without knowledge of site" [18] (p. 72). To gain knowledge of a site, landscape architects use a combination of direct engagement and secondary supporting research to perform a site analysis. Components of site analysis include physical (e.g., geology and climate), biological (e.g., vegetation), and cultural (e.g., current and historical land use) elements [19]. Site analysis draws together cultural and ecological knowledge of the past and present of a site to inform the design of its future.

Where circumstances allow repeated site visits over time, a comprehensive observational and experiential understanding of a site (and specific site elements) is created. Landscape architect academic Katherine Jenkins is an advocate for multiple site visits during the design process because she sees each visit as a "meeting of spatial and temporal trajectories in which both site and visitor are active" [20] (p. 6), so returning to a site over time reveals a site in 'motion'. For example, knowledge of a site at different times of day, in different types of weather, or different seasons will contribute to a better understanding of the site and, therefore, a more suitable design outcome [18].

The current study is pioneering in the Australian context and a starting point for comparisons of plant species and specific urban biotopes in spontaneous urban nature further afield. Our study is part of a larger research project that draws on environmental history, urban ecology, and design to recognise and explore cultural and ecological characteristics of spontaneous urban nature in Southwest Australia. The current case study focused on the spontaneous vegetation at a number of sites in two Southwest Australian cities with the following aims:

1. Initiate research-based literature on spontaneous urban nature in the context of Southwest Australia.
2. Establish an inventory of spontaneous urban vegetation and explore the cultural and ecological characteristics of these plants, as well as sites in motion.
3. Reframe the dialogue around and response to spontaneous nature through design-based narratives and proposals.

This study's aims were based on the research questions: What plants are present in sites of spontaneous nature in Southwest Australian cities, and what are the cultural and ecological characteristics of these plants and sites over time? And how can a design-based research approach communicate these characteristics and propose future responses to spontaneous nature in this context? Our study addressed the research questions by using vegetation surveys in four urban biotopes with spontaneous vegetation to establish an inventory of plant species, their natural ranges, and phenological changes in vegetation in two cities. Site surveys provided direct observations of cultural and ecological characteristics (e.g., maintenance practices, vegetative response, and urban fauna habitat), and when paired with supporting research (e.g., environmental histories), they contribute to a more holistic understanding of certain plant species and the surveyed sites. We used this design-based site-analysis approach, and the results of the vegetation surveys and subsequent discussion based on our analysis to reframe the dialogue around spontaneous nature in Southwest Australia, as well as highlight future potential (e.g., altering maintenance schedules around peak foraging habitat resources).

2. Materials and Methods

2.1. Study Areas

Fieldwork was carried out in two cities within the SWAFR, Albany and Fremantle (Figure 1, Table 1). Both cities have a similar colonial history and built environment, and their port activities were instrumental in trade (e.g., the introduction of plant species) from their inception in the early to mid-nineteenth century onward. The urban development of both cities has involved the large-scale removal of native vegetation and topographical change. Their urban landscapes are based on a grid system layout of European origin. They have compact urban precincts (around 2 km^2) located close to their port zones, which extend into suburbia with a mixture of public parks, private gardens, and street plantings that have traditionally followed the European Gardenesque style, dominated by exotic plant species [21]. The materiality of the built environment was initially dominated by locally sourced rocks (e.g., granite and limestone), which are still present in many buildings, walls, and other structures in both cities. Urban biotopes are a mosaic of the first, third, and fourth natures throughout their urban landscapes (e.g., native remnant bushland areas, lawns, flower beds, urban forests, verges, walls, and vacant lots), while the third nature, found on agricultural and pastoral plots of land, has largely been lost and built over as the urban footprint has expanded outward.



Figure 1. A map of Australia highlighting the Southwest Australian Floristic Region and the two survey locations, Albany and Fremantle (located within the Perth Metropolitan Area).

Table 1. Cultural, geographical, and climatic contexts of the two case study cities.

Study Areas	Albany	Fremantle
Location	35.0268° S, 117.8837° E	32.0518° S, 115.7551° E
Country/Custodians	Menang Noongar	Wadjuk Noongar
Geology	Alkaline peat soil/ Nornalup Complex	Spearwood dune system/ Tamala Limestone

Table 1. *Cont.*

Study Areas	Albany	Fremantle
Climate	'Csb' Koppen-Geiger Mild temperate	'Csa' Koppen-Geiger Warm temperate
Mean Rainfall [1]	925 mm	702 mm
Mean Temperature [1]	Min 11.8 °C–max 19.5 °C	Min 12.9 °C–max 24.8 °C
Colonial Settlement	NSW Penal Outpost 1826 Swan River Colony 1831	'Free settlement' Swan River Colony 1829
Urban Heritage	Industrial/trade port Heritage built environment [2]	Industrial/trade port Heritage built environment [2]

[1] Records for temperature in 1994–2024. Records for rainfall in 1994–2024. [2] Contains heritage buildings and areas within the urban precinct.

Albany and Fremantle are on country where Indigenous Australians have been the custodians for tens of thousands of years, but they were established as port cities during colonial settlement from the late 1820s onward (Table 1). Fremantle is located on Wadjuk country of the Noongar people. It sits within the Spearwood dune system on Tamala Limestone. It is a 'warm temperate' climate [22] or 'Csa' Koppen–Geiger climate type with long hot, dry summers and a mean of 702 mm annual rainfall, with an average minimum temperature of 12.9 °C and maximum of 24.8 °C [23]. Albany is located approximately 400 km southeast of Perth on Menang country of the Noongar people. The geology and landform of the area are alkaline peat soil on the Nornalup Complex, consisting of gneiss and granite. It has a 'mild temperate' climate [22] or "Csb" Koppen–Geiger climate type. The annual mean rainfall for Albany is 924.7 mm, with an average minimum temperature of 11.8 °C and a maximum of 19.5 °C [24]. These attributes were deliberately chosen to enable comparisons and contrasts in the fieldwork data between the two cities.

2.2. Urban Biotopes with Spontaneous Vegetation (Study Sites)

Site visits and vegetation surveys occurred at 24 sites across the two cities (Figure 2). Four site visits, including vegetation surveys, were conducted at each site during 2022, totalling 96 site visits (and surveys). Four biotope types were represented in the study sites: pavement cracks, walls, margins, and vacant lots (Table 2). The boundaries of each site were determined by the respective biotope (e.g., "An area of uniform environmental conditions providing a living place for a specific assemblage of plants and animals" [25]), and as such, the site areas varied accordingly. Site locations were first proposed using aerial imagery, followed by confirmation with an on-site inspection. All sites included in our study were unirrigated, had pedestrian access and public visibility, and were distinguished as one of the four biotope types. Details of the survey locations can be found in the Supplementary Materials (Table S1).

The surveys were timed to capture seasonal variations: the first set proceeded in late summer (February), the second in late autumn (May–June), the third in early spring (August–September), and the fourth in early summer (December). These surveys were deliberately scheduled to document a comprehensive range of species and life cycles, accounting for the specific climatic conditions of the study areas (e.g., long dry summers with rainfall during cooler months).

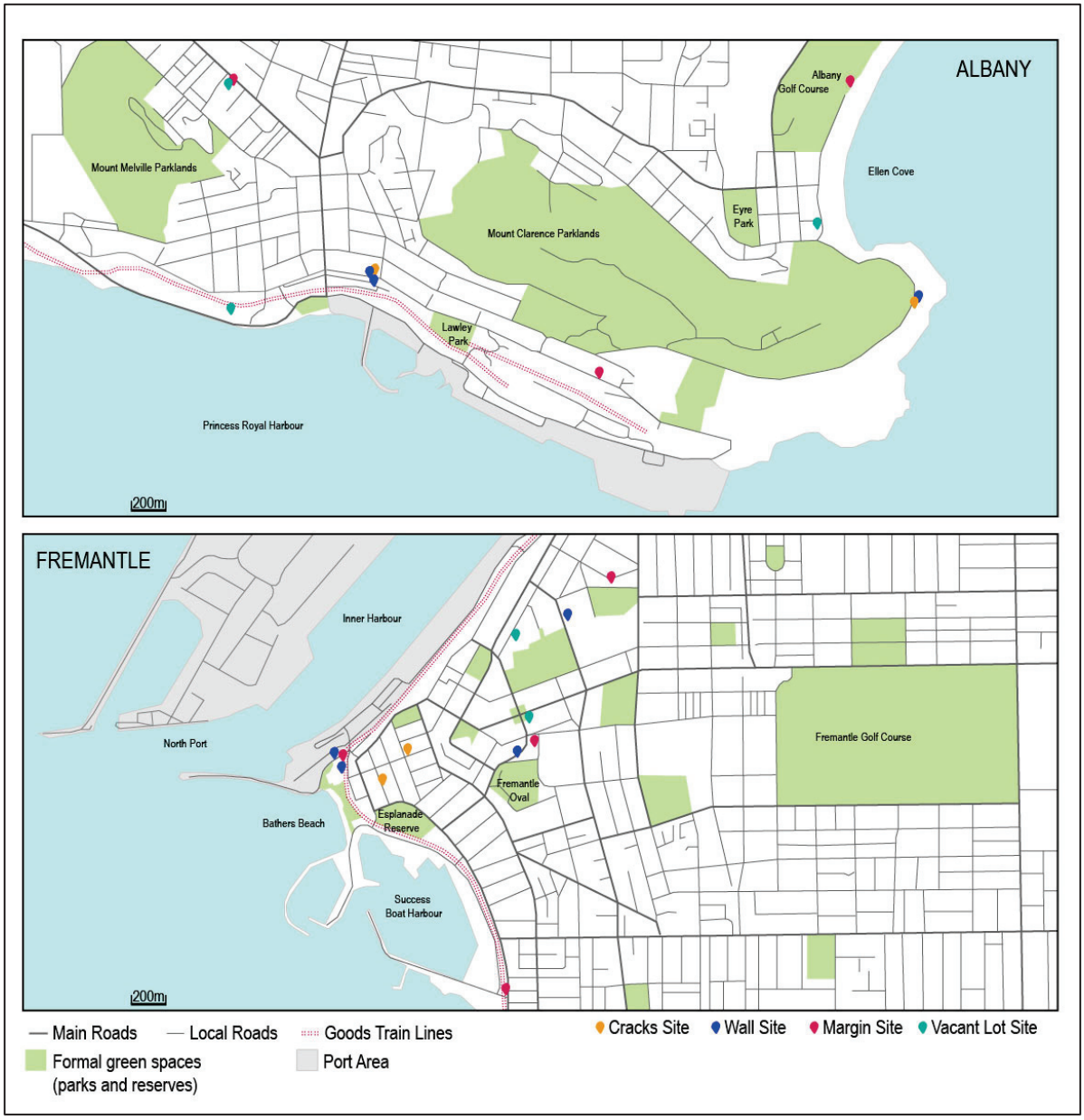


Figure 2. Map of Albany (**above**) and Fremantle (**below**) with site locations.

Table 2. Definitions of urban biotope types.

Biotope Type	Example	Definition
Pavement Cracks		Crack sites in our study were all located on paved pedestrian pathways. The paved surface area (including vegetation) was considered the site area. This falls under the 'microsite' typology of informal green spaces in Rupprecht et al. [5]. The crack sites measured 19–300 m^2.

Table 2. *Cont.*

Biotope Type	Example	Definition
Walls		Wall sites were defined as walls composed of one or more materials: bricks, rocks, and mortar. The total wall surface (including vegetation) was considered the site area. This falls under the 'structural' typology of informal green spaces in Rupprecht et al. [5]. Wall areas measured 13.2–50 m^2.
Margins		Margin sites were defined as linear spaces between distinct landscape features (e.g., pathways, roads, or other plant communities) with low-growing spontaneous vegetation. This falls under 'street verges' in Rupprecht et al. [5], but was not required to be within 5 m of a road. Margin sites were a maximum of 2 m in width and measured 25–400 m^2.
Vacant Lots		Vacant lots were defined as distinct parcels of cleared land, with no current buildings or visible site use and the presence of spontaneous vegetation. The word 'vacant' describes the lack of built form, not urban nature. This falls under the 'lot' typology of informal green spaces in Rupprecht et al. [5]. The vacant lot sites measured 475–4077 m^2

2.3. Survey Methodology, Materials, and Data Collection

Selective biotope mapping is small in scale, completed on-site by targeting specific biotopes, and aims to evaluate biotope values for protection [26–28]. Because of the detailed and specific focus of selective biotope mapping, it has been a vital component of nature conservation and planning strategies within the urban context [29,30]. Our study drew from the aims and intentions of selective biotope mapping combined with vegetation surveys in site analysis used as the basis of planting plans in landscape architecture [31]. For plant identification and nomenclature, the Western Australian Herbarium's Florabase was used [32].

In addition to vegetation surveys, site visits also recorded:

1. Observations of physical attributes of the site (e.g., soils, surface geology or built materiality, topography, site context, etc.);
2. Observations of cultural attributes, i.e., evidence of maintenance practices and the response of vegetation to them;
3. Site uses by people, pollinators, and other urban fauna (e.g., forage and habitat for pollinators).

2.4. Site and Vegetation Survey Analysis

1. Plants identified were used to create an inventory of spontaneous plant species with associated information from surveys (i.e., locations and biotopes where present) and supplementary analysis (i.e., plant families, native ranges, and life forms).
2. The species richness during each survey round, within each biotope, and in each city was determined.
3. The phenological states of each plant in each survey round were determined.

3. Vegetation Survey Results

A total of 145 species from 47 families were identified in this study (Table 3). The most common families were Poaceae (21 species), Asteraceae (19 species), Fabaceae (15 species), Brassicaceae (8 species), and Caryophyllaceae (6 species) (the complete plant inventory can be found in the Supplementary Materials Table S2).

Table 3. Plant species identified in fieldwork surveys.

	Study Total	Location Total	Location-Specific
Study total	145	-	-
Albany	-	90	50
Fremantle	-	95	55
Shared *	-	-	40

* Plant species present in both Albany and Fremantle.

3.1. Plant Species

Of the plant species identified, 62% were found in Albany and 66% in Fremantle. We identified 28% in both Albany and Fremantle, while 34% were unique to Albany and 38% to Fremantle (Table S2). Four species, *Cynodon dactylon*, *Euphorbia maculata*, *Hypochaeris radicata*, and *Sonchus oleracus*, were found in all biotope types in both cities (Table S3). In Albany, *Cenchrus clandestinus*, *Pseudognaphalium luteoalbum*, and *Plantago coronopus* were also present in all biotope types, as was *Erigeron bonariensis* in Fremantle (Table S3).

The total number of species in each city was lowest in late summer and peaked in early spring (Figure 3). The numbers of species in the two cities in late autumn and early spring were very similar, while Albany had 10–15 more species present during the two summer surveys.

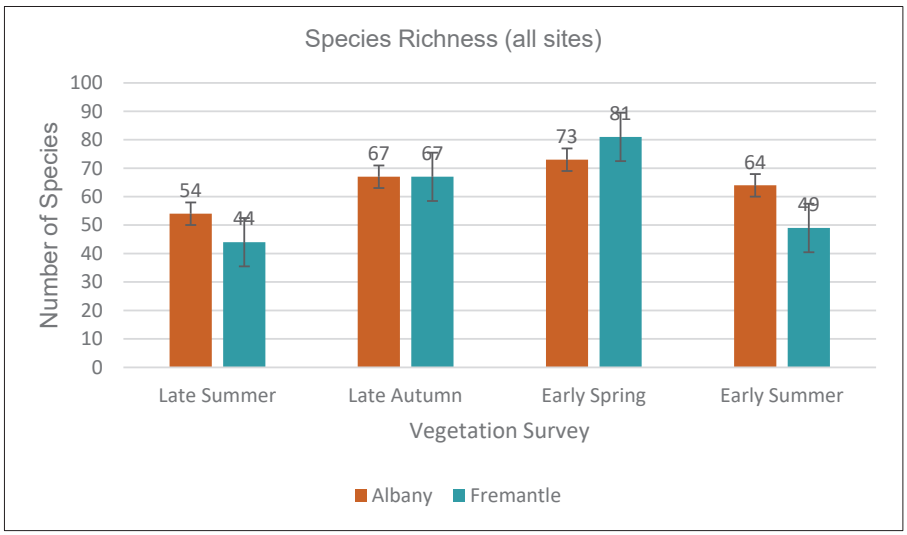


Figure 3. The total species richness found in each city and vegetation survey round during the study represented as bar graphs for easy visual comparison. The total number of species and standard error for each are shown.

The crack and wall biotope types had the lowest mean species richness (Figure 4) trend. In Albany, we recorded 12–25 species in each survey round, and in Fremantle, 6–12. Wall sites were similar in richness to cracks, with the exception of one Fremantle site that had 17–29 species in each survey round, which increased the total richness in Fremantle (27–37) considerably over Albany (13 species each survey with a total of 23 species). The margin and vacant lot biotope types followed a more pronounced seasonal trend, with the mean species richness lowest in late summer and a peak in early spring. For vacant lots, one Albany site was the most species-rich of all sites in the city (22–34 species).

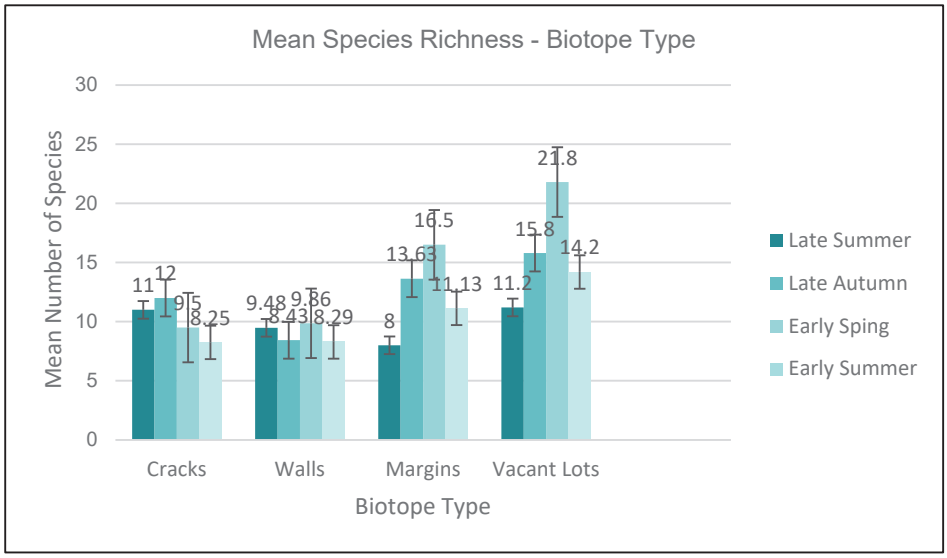


Figure 4. Mean species richness by biotope type in each survey round.

3.2. Plant Species: Native Ranges

The native ranges of the plant inventory were dominated by plants with native ranges in Mediterranean climates, including South Africa (18 species), locations clustered around the Mediterranean Basin (34 species), and the wider Mediterranean area (25 species) (Table S2). Many species had widespread native ranges, i.e., the range for *Polycapon tetraphyllum* includes Southern Europe, the British Isles, the Middle East, the Mediterranean, and India. Less than 10% (12 species) were of Australian origin. Four plant species were native to multiple geographies that include Australia but were considered naturalised outside of their normal range in this study, i.e., *Cynodon dactylon*, *Portulaca oleracea*, *Pseudognaphalium luteoalbum*, and *Tribulus terrestris.* Just over 5% (8 species) were native to Southwest Australia.

Australian native plant species identified at the genus level:

- *Acacia* spp., *Casuarina* species., *Eucalyptus* spp., *Scaevola* species.

Australian native plant species identified at species level:

- Native to SWA—*Adenanthos sericeus*;
- Native to WA—*Hardenbergia comptoniana*, *Lepidosperma gladiatum*, *Melaleuca huegelii*;
- Native to WA in part of the range, naturalised elsewhere—*Agonis flexuosa*, *Melaleuca lanceolata*;
- Native to WA and the southern regions of Australia—*Caladenia latifolia*;
- Native to coastal regions of WA, southern Australia, Africa, and New Zealand—*Ficinia nodosa*.

3.3. Life Forms

In the surveys, 50.34% of the species found were annual, and 38.62% were perennial (Table 4). *Oenothera glazioviana* was the only purely biennial species, and *Malva arborea* was the only species that could be annual, biennial, or perennial in form. The other 9.66% were a combination of annual and biennial or annual and perennial. All species considered native to the study areas were perennial or woody (shrubs and trees).

Table 4. Number of species as life forms.

Life Form	Number of Species
A [1]	73
A [1] or B [2]	3
A [1], B [2], or P [3]	1
A [1] or P [2]	11
B [2]	1
P [3]	34
P (S/T) [4]	22

[1] A = annual, [2] B = biennial, [3] P = perennial, [4] P (S/T) = woody shrub or tree [31].

3.4. Phenology

The combined phenological data for all sites exhibited a general trend toward a peak of flowering plants in early spring (70 species) and a low- in late autumn (26 species) (Figure 5). These results are consistent with the growth habit of most annual species in Southwest Australia, which establish over winter before flowering through spring and into summer. The first surveys in late summer had the least number of species (82), but over half of the species in bud and/or flower (47). In contrast, the late autumn survey had 103 species, with 26 in bud and/or flower. The number of species fruiting and/or with seeds peaked in early summer (34 species), which is consistent with seeds following the peak flowering time of spring.

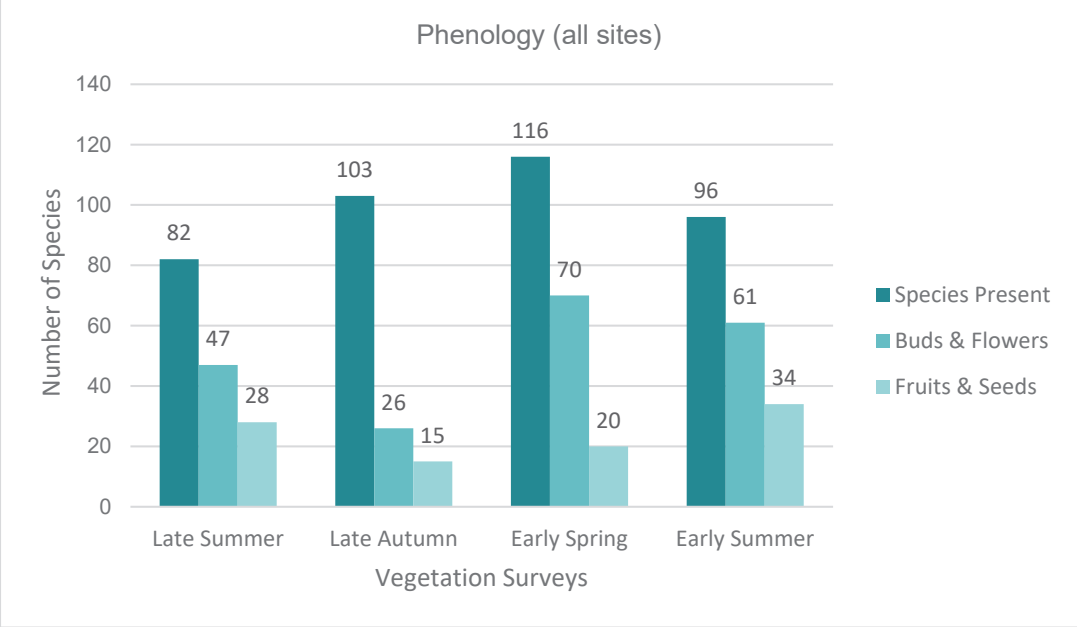


Figure 5. The phenological stages exhibited by plant species at all sites during this study.

4. Site Analysis and Discussion

4.1. Sites and Species in Motion

Many spontaneous species are successful because they can thrive in a wide range of urban situations. Other species require more specific conditions (e.g., soil pH levels) to survive [33]. The findings from our study support this statement, with less than 10% of the plant species found being native to Australia. This finding is similar to the floristic study of urban areas in northern New Zealand by Asmus and Rapson [34], which had 11% native species, but is in contrast to studies conducted in European countries, where a much larger majority of spontaneous species were native. For example, a study by Kansta et al. [35] in Greece, found that nearly 90% of the species were native to the study city of Ioannina. Australia and New Zealand share a similar pattern of abrupt changes to the pre-colonial landscape and environment, with plant and animal introductions, built structures, and land use changes that mimicked 'home', i.e., England, bought about by European settlement [33,36,37]. Therefore, while the climate, geography, and native ecosystems of New Zealand and the southwest of Western Australia differ significantly, their shared cultural histories have led to common urban situations and similarity in introduced spontaneous plant species. In our study, 53 of the 145 species were shared with the Asmus and Rapson study. The city of Ioannina, (Greece) has the same hot-summer Mediterranean climate as Fremantle and shared 34 species with our study (e.g., *Nerium oleander* and *Olea europaea*), largely native to the Mediterranean.

The species found in the widest variety of situations in our study were the introduced species *Cynodon dactylon*, *Erigeron bonariensis*, *Euphorbia maculata*, *Hypochaeris radicata*, *Plantago coronopus*, and *Sonchus oleraceus*. *C. dactylon* and *S. oleraceus* have interesting environmental histories, and their cultural and ecological characteristics are worth further consideration.

4.1.1. *Cynodon dactylon*

Cynodon dactylon originated in sub-Saharan Africa but has been introduced to the tropics and beyond worldwide and now thrives in many climates and urban situations. Some authors consider it the native species of *Cynodon* found in the Kimberly in Northwest Australia [38], but in Southwest Australia, it is thought to have been introduced directly from Britain during the mid-nineteenth century [39] and via the East Indies [40]. It has been advertised for sale as a lawn grass in Perth newspapers since the early twentieth century [41] and was so common by that time that it was widely considered native [42]. In Southwest Australian cities today, *C. dactylon* is simultaneously used as a lawn grass in parks, gardens, playing fields, and verges (of the third nature), considered a significant weed of remnant bushlands and wetlands (of the first nature), and, as in our study, commonly found in various biotope types with spontaneous vegetation (of the fourth nature). Its ability to withstand long periods of drought, provide sustenance to urban fauna over summer months (when annual grasses have died off), and control erosion in loose sandy soils and banks, and its popularity as a hardy lawn grass, mean it has and will continue to thrive in a wide variety of urban situations in Southwest Australia.

4.1.2. *Sonchus oleraceus*

Sonchus oleraceus, an annual plant, was another frequently occurring species found in all four biotope types and survey rounds of the current study. It is one of the most widespread weeds in the world [43] and has naturalised in many regions [44], so the species' prevalence in our study was not unexpected. *S. oleraceus* can germinate, flower, and set seed in a wide variety of situations, including wet, dry, sunny, or shady positions [45] at any time of the year in moderate climates [46], which was evident by its continued presence in a

variety of phenological states in our study. Locally, an 1837 report of the Swan River Colony by military surgeon Dr William Milligan noted it as a native edible and a good substitute for spinach [16]. Although the native status was incorrect, Milligan's presumption indicates that it had already been introduced and was common enough around colonial settlements to be considered native in the early years of European settlement and, as such, it is part of the environmental history of urban landscapes and nature in Southwest Australia. One of the ecological benefits of *S. oleraceus* is its ability to build up soil and nutrients for other plants by ploughing through surface soils with an extensive root system [46]. It is high in vitamin C, calcium, copper, iron, and potassium and a favoured food source for various fauna, including rabbits, birds, aphids, and pollinator insects [46,47]. This makes it a valuable plant to consider in the context of habitat and food sources for pollinators and other urban fauna in Southwest Australian cities.

4.1.3. Species and Site Contexts

Asmus and Rapson [34] found that small differences within local urban environments, combined with random establishment opportunities (and other vectors), influence the presence of different plant species. Some notable examples of this were found in our study, for example, *Caladenia latifolia* (pink fairy orchid) and *Pisum sativum* var. *saccharatum* (snow pea) (Figure 6). The margin site where *C. latifolia* grew in Albany was adjacent to a pedestrian pathway within a strip of remnant coastal bushland between a beach and a golf course. The margin biotope was maintained by a ride-on mower and frequent pruning of the bushland to keep the pathway open, providing a consistently low vegetation height, easy availability to sunlight, a low level of trampling, and a high level of shelter. In this case, the original soil complex and seedbanks appeared to be preserved, and the maintenance practices supported a situation for *C. latifolia* seeds to germinate and disperse by wind along the margin site. In contrast, the *P. sativum* var. *saccharatum* present at a vacant lot site in Fremantle is likely due to a novel set of circumstances that are unlikely to be repeated. The site is on a street with residential and commercial properties, a large sports field, tennis courts, and a carpark. Pedestrians walked through the site frequently during site visits, and we postulate that a chance introduction from discarded food by a pedestrian or garden waste from a nearby home at the right time of year allowed for successful germination of the plant.



(**a**)

Figure 6. *Cont*.



(**b**)

Figure 6. *Caladenia latifolia* in flower at a margin site in Albany (**a**) and *Pisum sativum var. saccharatum* in flower and fruiting in Fremantle (**b**) during fieldwork (photos: K. Stewart).

4.1.4. Native and Naturalised Australian Species

The species in our study were predominantly introduced species that have been able to take advantage of opportunities to establish in urban situations that most native species have not. Most introduced species were annual, while most Australian species were perennial or woody plants. Most of the native species in our study were also known to have a widespread range, and are used in revegetation projects or sold commercially as ornamentals, indicating their success in cultivation and tendency to adapt and thrive in more urban situations than other native species. For example, *Melaleuca lanceolata* and *Agonis flexuosa* have naturalised outside their natural range and into biotope types they are not normally associated with in Western Australia, due to their widespread use as ornamentals and for rehabilitation and amenities [48]. *Ficinia nodosa* has a widespread coastal range within and outside of the Australian continent. *Adenanthos sericeus* had the smallest natural range of the native species in our study, limited to the coastal sandhills and outcrops between Albany and Esperance [48]. Still, it has been successfully cultivated and sold as a garden ornamental throughout Australia. *Caladenia latifolia* (Figure 6) is native to the southern parts of Australia. This finding supports the existing literature that most native Southwest Australian species struggle to adapt to the ongoing anthropogenic disturbances of urban landscapes [14]. However, some can adapt through means such as native seedbanks and cultural influences (e.g., maintenance activities that eliminate competition).

4.2. Biotope Types and Survey Sites

Observations during site visits made it clear that there were differences between species and maintenance practices (e.g., mowing) in different biotope types. Vacant lot and margin sites generally had larger soil surface areas for plants to grow on, with less frequent or invasive maintenance regimes than crack and wall sites (e.g., mowed rather than sprayed with herbicides), which resulted in more species, more vegetation, and a wider variety of phenological stages present at each survey. A more detailed discussion of the analysis of biotope types and specific sites follows.

4.2.1. Pavement Cracks

The crack biotopes had the highest pedestrian traffic and were the most frequently maintained (i.e., with hot water high-pressure spray). This resulted in plants with primarily compact and prostrate forms, and very few plants were in bud, flower, fruiting, or going to seed during the surveys. Only four species had at least one plant in any of these

phenological stages over the study period in Fremantle (*Portulaca oleracea*, *Lolium* spp., *Sagina procumbens,* and *Polycarpon tetraphyllum*). In Albany, the number of species in different phenological stages was higher. For example, in the first survey, 15 of the 25 species had plants with buds or flowers. It may be that the cooler climate and higher rainfall in Albany account for the higher number species in this biotope. The crack site with the most species was located in Albany and surrounded by a car park, a small lawned area, a low retaining wall, and native coastal vegetation. It was the most exposed of all the crack sites and the only one immediately adjacent to other urban biotope types from the first and third natures. Several species in the crack site were also present in the walls and lawn areas surrounding the site, reiterating the fluidity of the movement of species between different 'natures' and biotope types in a local context.

4.2.2. Walls

The number of species and phenological states of wall sites were similar to the crack biotope, except for one site in Fremantle, with 17–29 species in each survey. This site demonstrated the potential for mural ecologies in established wall biotopes. In *The Ecology of Urban Habitats*, urban ecologist Oliver Gilbert [49] discusses the increased diversity of established mural vegetation of walls over 100 years old. He explains that they are more likely to be made of materials such as natural rock, bricks, and mortar, and with the element of time, cracks and crevices develop in the mortar, resulting in soil and nutrient build-up, an increase in vegetation coverage, and seed dispersal, which creates a diverse mural ecology. The wall site in Fremantle (Figure 7) is part of an aeolianite limestone headland, Arthur Head, which was quarried, excavated, and built upon (and some parts demolished) during the nineteenth century by European settlers, changing the topography dramatically [50]. The area then went through a period of abandonment and, more recently, has undergone conservation work on the remaining buildings, pedestrian and vehicular access stairs, paths, and roads, along with stabilisation of the quarried rock faces.



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

Figure 7. The outlier wall site in Fremantle with early settler garden variety plants including *Foeniculum vulgare*, *Ipomoea indica*, *Nerium oleander*, *Vitis vinifera* subsp. *vinifera* (**a**), *Ficus carica,* and *Polygala myrtifolia* (**b**) during fieldwork (photos: K. Stewart).

The study site (Figure 7), with a high point of around 4 m, is primarily sheltered from harsh coastal winds by surrounding warehouses of the port area. The vegetation here differs from that found on other outlooks of the headland's walls and cliffs. Many of the perennial species of the site are early colonial food and ornamental garden plants, likely originating from 19th-century cottagers' gardens above [51]. These species include *Vitis vinifera* subsp. *vinifera*, *Ficus carica*, *Foeniculum vulgare*, *Ipomoea indica*, *Polygala myrtifolia*, and *Nerium oleander*. The perennial species at the site were severely pruned during one site visit and a profusion of new growth on these plants was observed during subsequent visits.

These observations demonstrate a site in motion, with plant species influenced by the site's history and demonstrating ongoing vegetative responses to maintenance.

4.2.3. Margins

There was a lot of variability in plant species in the margin sites. All margin sites had relatively low growing habits during the initial site visit. This habit and the dominating species of each site varied widely during subsequent visits. One site in Fremantle, located between a carpark and a pedestrian (and bike) path, was highly trampled and regularly maintained. Like in the crack biotope type, the vegetation was sparse and predominately seedlings or young plants, with little variability in phenological stages during our study. Another site in Fremantle, bordered by a metal security fence and a pedestrian (and bike) path, had more sporadic maintenance practices. During one site visit, several mature *Erigeron bonariensis* had been pulled out of the ground and put in a pile, but they still grew and flowered freely elsewhere on the site. Perennial grass (lawn) species tended to dominate the sites where they were present, but their coverage varied widely over the year and depended on the presence of annual species.

4.2.4. Vacant Lots

Vacant lot sites had the greatest variation in the number of species present throughout our study and were the most susceptible to anthropogenic factors, i.e., land use changes. A site in Albany (with no evidence of maintenance practices) had the highest number of species of all sites in our study. Distinct microclimatic conditions at the site also led to different plant combinations in different areas. The site was at the bottom of a steep slope adjacent to a main road and bordered by retaining walls on three sides. The walls provided shade and wind protection, with seasonally waterlogged soils at their base and which species such as *Cyperus congestus*, *Holcus lanatus*, and *Rumex crispus* flourished. In the open sandy areas, *Cakile maritima*, *Diplotaxis muralis*, *Erigeron canadensis*, and annual grass species grew sporadically. The vegetation at this site demonstrated Sukopp's [4] position that unique microclimatic conditions of the built environment create specific sets of circumstances that determine which plants grow where and in which conditions, even within the same biotope type. Another site in Albany became a construction site during our study, with a series of areas fenced off, dug up, and infilled over subsequent surveys. The activity on the site illustrates the abrupt land use changes in urban landscapes.

One site in Fremantle was almost bare of plants (8 species) during the first site visit but peaked in the number of species (28) with considerably more vegetation in early spring. Another site in Fremantle was primarily covered by vegetation in the first three site visits (dominated by *Cynodon dactylon*) but had a sharp drop in vegetation at the last visit, likely due to anthropogenic factors, i.e., the site was used as an ad-hoc carpark toward the end of this study.

4.2.5. Pollinators and Other Urban Fauna

Insects, spiders, birds, reptiles, and mammals were observed in all biotope types in our study. Many insect pollinators (i.e., ants, aphids, bees, butterflies, caterpillars, cicadas, flies, hoverflies, ladybirds) and birds including Australian ravens (*Corvus coronoides*), Australian magpies (*Gymnorhina tibicen*), magpie-larks (*Grallina cyanoleuca*), silver gulls (*Chroicocephalus novaehollandiae*), singing honeyeaters (*Gavicalis virescens*), and willie wagtails (*Rhipidura leucophrys*) were seen foraging at the survey sites and their surrounds. The European honeybee (*Apis mellifera*) (Figure 8), naturalised in Australia, was especially common at margin and vacant lot sites. In Albany, a native King's skink lizard (*Egernia kingii*), fed on spontaneous vegetation growing between cracks close to two study sites. In Fremantle, rats (*Rattus*) foraged among fruiting grapevines at a wall site. Birds were the most noticeable

fauna during site visits, especially at vacant lots. Their ease of movement within and through various urban biotopes and our study sites demonstrates that different urban biotopes, and natures, contribute to a diverse urban nature and that nectar and habitat resources should be considered further in regard to spontaneous vegetation in Southwest Australian cities.



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

Figure 8. A European honeybee (**a**) and King's skink lizard (**b**) foraging at sites in Albany during fieldwork (photos: K. Stewart).

4.3. Reframing the Dialogue Around the Fourth Nature

The site analysis of urban biotopes with spontaneous nature in our study revealed that this nature exists in Southwest Australian cities and contains plants and biotope types that are suited to urban situations and exhibit natural ecological cycles. The amount of vegetation and number of species at different sites vary, but this vegetation consistently comprises green spaces (i.e., contain plants) that survive and thrive without irrigation and fulfill a range of ecosystem services. They also provide forage and habitats for urban pollinators and other urban fauna, which are important elements of urban nature and cities. They are sites in motion: their vegetation changes, with different species and life forms over the seasons. They are populated by plants suited to the sites they grow in. They germinate, flower, fruit, and set seed with or without anthropogenic actions (e.g., maintenance and land use changes). The sites in our study were not occupying spaces where native biotopes would be, and were in some form, temporary.

There is the potential to enhance ecological aspects of the sites in our study (and more broadly sites with spontaneous nature) via further examinations of foraging resources in response to altered maintenance practices (e.g., mowing after peak flowering periods and decreasing the use of herbicides). There is also the possibility of exploring other ecological aspects not considered in this study, e.g., how unirrigated vegetation contributes to reducing the urban heat island effect. In addition, the environmental histories of plants, people, and places (e.g., of European settlement, past and current plant uses by people, pollinators and other urban fauna) can signal new perspectives on plants that are already part of the urban nature in Southwest Australia. Reframing the aesthetic perceptions of these spaces may also contribute to more interest in this nature, for example, the resilience of plants allowing them to germinate in the harsh environment of wall biotopes (Figure 9) where nature would otherwise be absent.



Figure 9. *Cymbalaria muralis* in flower and moss growing in the mortar of a wall site in Albany during fieldwork (photo: K. Stewart).

4.4. Study Limitations

The number of survey sites used in this study was small; therefore, the scope of our study does not provide an exhaustive inventory of spontaneous species in Albany, Fremantle, or Southwest Australia, or a complete representation of all biotope types with spontaneous urban nature. Comparisons made between sites and biotope types had some limitations. For example, we did not perform calculations on the species richness of different sites considering the variability of site sizes, species-area (plot) sizes, and relationships [52].

The schedule for conducting vegetation surveys throughout the year did not necessarily coincide with maintenance schedules by local governments, and we did not specify maintenance methods as a precursor to site selection. So, while different vegetative states provided some insight into the relationship between cultural interventions and vegetative responses, we suggest that future studies arrange for site visits before and after specific maintenance practices to gain more specific insights into sites in motion in this regard.

5. Conclusions

This study has initiated research-based analysis of spontaneous urban nature in Southwest Australia. It took a design-based site analysis approach familiar to landscape architecture to explore and communicate cultural and ecological characteristics of sites in motion, create a plant inventory, and reframe the dialogue around spontaneous nature. This approach led to specific findings (e.g., species presence and their environmental histories and current statuses, sites as foraging resources for urban pollinators and other fauna, and the temporary status of sites with spontaneous nature) and identified potential (e.g., altering maintenance schedules to retain foraging resources). However, the scope of our study meant that quantitative comparisons between biotope types and cities were limited, as was the application of our findings to all spontaneous urban flora in Southwest Australia. We suggest that further research is merited into this currently overlooked part of urban nature, and we propose that future studies should include both small-scale selective site analysis approaches and large-scale quantitative vegetation survey methods (e.g.,

comprehensive biotope mapping), to further our understanding of the characteristics and potential of the fourth nature in the context of Southwest Australian cities.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land14030467/s1. Table S1: Site details; Table S2: Combined species list; Table S3: Species, biotope, location.

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Abbreviations

The following abbreviations are used in this manuscript:

SWA	Southwest Australia
SWAF	Southwest Australian Floristic Region
WA	Western Australia

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Review

Toward a Construct-Based Definition of Urban Green Space: A Literature Review of the Spatial Dimensions of Measurement, Methods, and Exposure

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Abstract: Interdisciplinary research has significantly advanced our understanding, benefits, and measurements of Urban Green Space (UGS). Further, the rapid expansion of research on this topic has resulted in a diverse array of definitions, which can rely on implicit assumptions without a formal definition. This variability highlights the need for a carefully structured framework to refine and combine these definitions. This narrative review examines constructs underlying UGS, particularly focusing on the spatial aspects of how we spatially measure UGS, the measurements of UGS, and how we define exposure; the latter focuses on two methods: viewsheds and image segmentation. Our findings reveal a shift in UGS measurement focus, moving beyond simple quantification of how much green space exists, to incorporate visibility, accessibility, and availability dimensions. Furthermore, advancements in computational tools, including artificial intelligence-driven methods, now enable high-resolution visibility measurements on a city-wide scale, supporting epidemiological research and urban development. These insights aim to guide researchers and practitioners in selecting suitable methodologies and datasets, as well as explicitly defining UGS in their work through a construct-based approach.

Keywords: greenspace; urban; GIS; data collection; health; NDVI; plan view; perspective view; viewshed; green view index

1. Introduction

Global urbanization continues to rise rapidly [1]. Urbanization can reduce exposure to nature [2] and limit opportunities to experience green spaces, despite evidence that existing Urban Green Spaces (UGS) positively affect residents' well-being [3–11]. Nonetheless, studies also highlight the lack of accessible green spaces across urban districts [12–14]. To better understand the relationship between humans and UGS, researchers developed several ways to measure UGS allocation, accessibility, and visibility. Studies include perspective-view approaches using subjective methods [15,16], as well as more objective approaches such as remote sensing. The latter has facilitated the development of epidemiological and population-level approaches [17,18]. Regardless of the method, urban planners have sought measurement tools to support decision making, including the monitoring and improvement of UGS [19,20].

The literature uses both "green space" and "greenspace", with variations often reflecting disciplinary perspectives and trends [21]. While we acknowledge these differences,

for consistency, we use "green space" throughout this paper. Using a narrative review process, we strive to synthesize the vast recent scientific literature on UGS by building a UGS construct that clarifies the core elements that constitute UGS—with emphasis on the spatial aspects of UGS. The purpose is to help clarify what UGS measurements are and how they are used, as well as to identify the various scales and constraints of UGS.

To guide our examination of the literature, we pose the following key question: (1) How can we define UGS that considers its wide variety of uses and interpretations? We then ask the following secondary questions: (2) What are the core methods for analyzing UGS, and (3) the key datasets used to measure UGS? Our literature review explores these questions, emphasizing the effects of greenness exposure and the utilization of digitized datasets in geospatial applications for measuring UGS. We develop a framework that presents an overview of the various geospatial and analytical methods employed in the UGS measurements. The framework includes a detailed discussion of the latest techniques for measuring green space and a comprehensive exploration of quantitative methods using GIS-based datasets to analyze UGS. Through this approach, we aim to contribute to a better understanding of UGS measurement and its applications across different fields. In the following subsections, we highlight the significance and importance of UGS, as well as methodological developments and challenges, as these two topics help establish a foundation for our methodological approach.

1.1. Significance of UGS Measurement

UGS typically falls within land use planning as open areas designated for parks and other natural settings [12,22]. However, its definitions and concepts often can vary across different disciplines [23]. For instance, some studies in the health sector define UGS based on administrative criteria, ranging from small gardens of a nursing home to multiple parks of a school district [24,25], while others focus on the overall greenness of geographic context from residential areas [26]. In environmental planning and ecology, the definition of UGS takes on an even broader definition to not only include cities but also regions [27]. Beyond differing definitions of scale, UGS can take on different definitions of function. For instance, UGS can act as a gathering space which may be used to advocate for the inclusion of sociocultural issues [6,28,29]. Consequently, the multifaceted approaches to defining UGS across diverse fields and studies underscore the challenge of establishing a uniform definition, reflecting the complexity and contextual nature of UGS interpretation [12]. Given the diverse interpretations of UGS across different disciplines, the measurement of UGS broadly captures greenery within study areas and often relies on geospatial datasets to assess physical or visual exposure to these spaces [30]. For instance, some studies have measured the physical extent of vegetation in cities such as Munich, Germany [31], Los Angeles, U.S. [32], and Montreal, Canada [33], using these datasets. Other studies have assessed proximity to UGS, such as public parks or semi-natural areas, to explore their association with physical activity [34] and mental health [35]. Despite these efforts, challenges remain, particularly in capturing how residents experience UGSs and the physical or visual interactions that shape urban life [6,8]. To address these limitations, measurements using GIS applications have advanced by improving data collection, processing, and analysis through a variety of means [36].

1.2. Methodological Developments and Challenges in UGS Measurement

These developments have enabled studies employing objective and quantifiable UGS measures, which can be broadly categorized into two groups. The first group focuses on developing original measurements or metrics, while the second group focuses on applications of these measures. Studies in the first group are often based on advanced remote

sensing data [30,37]. Technical advancements have made fine-grained, high-resolution data available, allowing for the use of more complex algorithms [38,39]. Developing original measures and utilizing diverse data have been combined in various interdisciplinary approaches, such as using social media for visibility analysis [40], a GPS accelerometer for nearby park accessibility [41], and machine learning algorithms to identify preferred urban spaces [42]. In particular, various artificial intelligence techniques integrated with image datasets captured by satellites or ground-level devices enable the distinction between green spaces and built areas at the city scale [43–45]. Those approaches lead to further advancement of UGS measuring techniques, such as digitizing individuals' perceived spaces [46–49].

Studies in the second (applied) group aim to better understand the implications of UGS measures on residents [26,50,51]. In these studies, UGS datasets are considered one of the variables, among other factors like socioeconomic status [52], mental health [53], and equity [13]. For instance, in epidemiological studies, they may use UGS datasets [54] or develop specific measurements to provide predictive variables for key health-related objectives [55]. The studies in this group concentrate on identifying what environmental factors affect their participants or how the UGS associates as a mediator [8,56]. Consequently, whether a study has developed a method for measuring UGS or has used the existing datasets, a critical point is that measuring and collecting quantified green space is consistently required in various fields of study.

Given the wide range of uses and methods associated with UGS measurement, there have been theoretical arguments about different kinds of data and related measurement techniques [27]. The literature provides examples of studies that used different source data to measure vegetation (e.g., NDVI derived from Landsat, the US Forest Service Percent Tree Canopy, and the National Land Cover Database). Meanwhile, advancements in technology mean new methods are continuously developed. For example, artificial intelligence-based feature recognition using Google Streetview [42,54] offers a very different approach because it measures green space in perspective view, rather than from above the city. However, this source variability complicates longitudinal studies, as UGS measures may not be consistent between datasets, making it challenging to observe changes over time [56,57] and to conduct quantitative meta-analyses [51]. Additionally, the absence of a specific framework for UGS datasets can make deciphering these data more challenging for planners and policymakers. For instance, the amount of UGS allocated for recreational use differs significantly from UGS displayed for urban aesthetics, yet both are commonly referred to as UGS [58,59]. Based on the findings of this review, the gap between dataset developers and end-users in understanding these distinctions has received little investigation in the context of UGS. To better understand the range of different uses of UGS, it would be helpful to create an organizational schema that assists individuals in identifying the data, methods, and techniques they use and ensures researchers and practitioners are aware of any related limitations.

Accurately measuring UGS, particularly near residential areas, has become increasingly important as these datasets are applied across various disciplines. In epidemiology, for instance, numerous studies have explored the relationship between UGS and population health outcomes [55,60]. While other fields have examined visual impact assessment [61] and the characteristics of urban areas [13,62], health-related research frequently refers to UGS as a *greenness exposure assessment*, emphasizing human interaction with green spaces [8]. This terminology reflects a broader shift in the field towards more human-centered analyses [36,50]. While measuring the perception of greenness remains subjective, the objective UGS measurement continues to provide valuable data for researchers, admin-

istrators, and planners. Such data can serve a wide range of purposes, underscoring its significance beyond mere measurement.

Furthermore, UGS data find application in exploring the potential health-promoting effects of green spaces [51] and ecosystem services provided by green infrastructure to aid urban planning efforts [63]. It demonstrates that understanding how these data are created and used across studies and disciplines can help bridge gaps between the developers of data sources and the users. The variations of UGS measures and definitions across fields further highlight the need for a more universally accepted terminology (or at least a higher-level representation of similar and different definitions). This seeks to clarify these differences and provide a framework to better understand the range of UGS measures and applications.

Lastly, having an organized framework could contribute to achieving Sustainable Development Goals (SDGs) by serving as an indicator of target goals. For example, Goal 11, which emphasizes making cities inclusive, safe, resilient, and sustainable, specifically highlights the importance of increasing public spaces as urban green infrastructure [64]. Achieving this goal necessitates the quantification and analysis of such spaces for equitable access and effective management [64,65]. A structured UGS measurement framework can assist the data users in selecting appropriate measures and understanding the factors that influence datasets.

2. Methods

We conducted a narrative review to explore the range of different measurements and subsequently produced a conceptual framework to represent this variety. A narrative review is advantageous when the topic spans various fields and linked information needs reinterpretation [66,67]. For example, UGS measurements are linked to geography, computer science, urban planning, and epidemiology. Our narrative review integrates findings from research across varied methodologies and theoretical approaches, focusing on the overall implications and improving our theoretical context for how we define UGS. PRISMA is a highly effective review approach, but its focus tends to be on the quantitative assessment of trends, patterns, and knowledge expansion of a particular topic. This model could be useful for UGS. However, a narrative review can be beneficial given the lack of theoretical constructs, the extensive range of methodologies, and the multidisciplinary of the topic [68]. The review process involved multiple iterations and revisions to ensure a thorough screening of articles. Indeed, as we identify in Figure 1, we also followed a structured framework, but it was also important to have the flexibility in our review to explore literature outside a constrained criteria search. Our primary focus was to extract key constructs and measurement approaches from the literature, starting with pre-existing review articles. Figure 1 below outlines our overall process.

The review used Google Scholar and Scopus to access a comprehensive range of peer-reviewed literature. While we acknowledge potential redundancy between these databases, we decided that using those ensures broader coverage. As noted in the introduction, users working with UGS datasets typically rely on available geospatial data within their study areas when initiating data collection. This means that studies employing UGS data are abundant, but the data collection process is often guided by practical considerations rather than specific theoretical foundations. Given this, researchers primarily select UGS datasets based on their study objectives and the availability of up-to-date data, rather than adhering to predetermined theoretical criteria. Since this review focuses on methodological applications rather than theoretical evaluations, Scopus provided sufficient coverage without requiring expansion to other databases (e.g., Web of Science or PubMed).

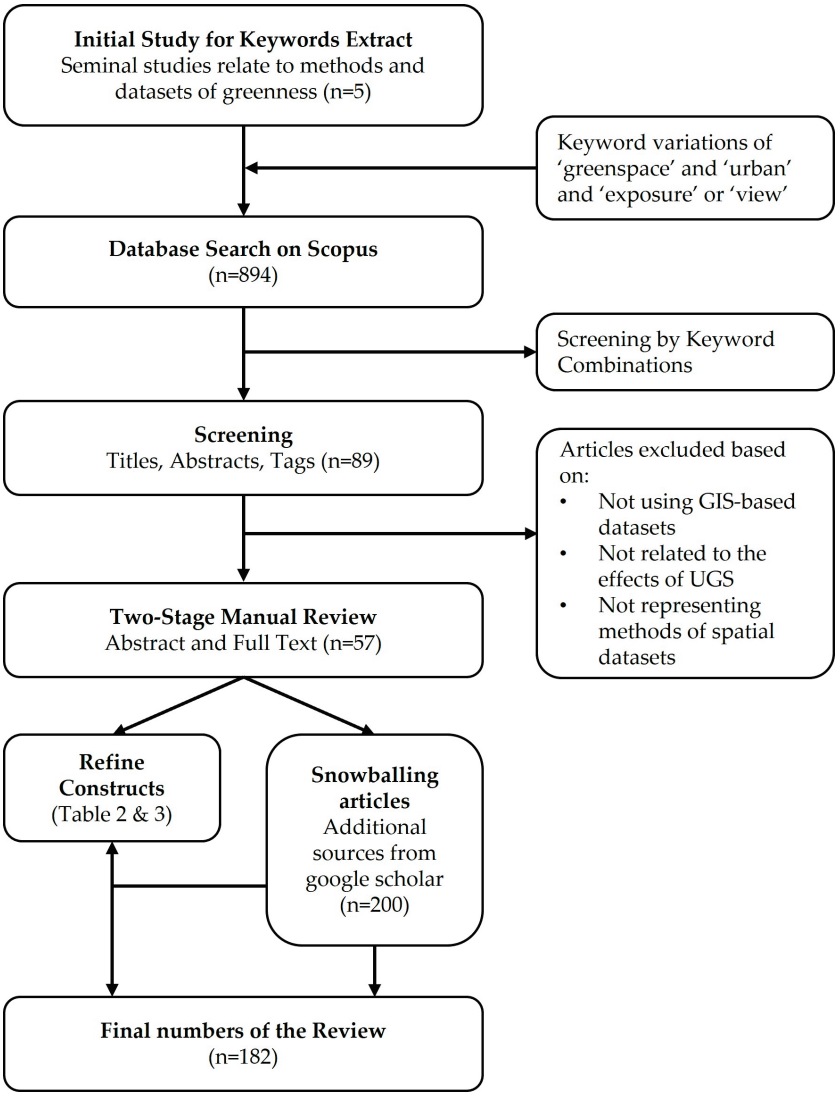


Figure 1. Search approach and the process of the narrative review.

To examine the methods employed in urban areas, initially, we used Google Scholar to search seminal studies (e.g., [8,36,38,56,69]) related to UGS measurements as a literature review. The retrieved literature contains methods for measuring or assessing greenness in certain spatial areas. Through the seminal studies, we extracted search keywords for searching in the Scopus search engine. We iterated through combinations to finalize the list of keyword terms. The following are the search terms: "greenspace" or "green space" or "greenness" or "greenery" or "green infrastructure" and "urban" or "city" or "metropolitan" and "exposure" or "visibility" or "view" or "viewing" or "visual". We included articles written in English and published in peer-reviewed journals. The keywords search on Scopus retrieved 894 documents. A quick review of these titles (out of 894 documents) resulted in a majority of that seemed to be irrelevant to the purpose of this research. We suspected this was due to the broad range of topics that can be covered under keywords such as "green", "urban", and "view". Additionally, due to the interdisciplinary nature of our research questions and objectives, identifying relevant literature using only specific academic terms may have led to unexpected results. For example, terms such as "green space exposure", "nature experience", "perceived natural landscape", and "green space evaluation" carry distinct definitions but can be applied differently, despite often using similar GIS-based data representing vegetation.

Therefore, we needed to narrow the literature to more directly relevant articles. To accomplish this, results were imported into an Excel file, where we screened the literature by filtering titles, abstracts, manual tags, and automatic tags for the selected keyword combinations (Table 1). We selected studies that met at least one of the three categories of terms. This resulted in 89 articles.

Table 1. Keyword combinations for screening literature.

Green Space-Related Terms	Spatial Context Terms	Measurement-Related Terms
greenspace		exposure
green space	urban	[1] measur-
greenness	city	visibility
greenery	metropolitan	[2] view-
green infrastructure		visual

"green" was an essential term, inevitably including variations due to its generality. [1] "measur-" was used to include studies employing independent data collection methods. [2] "view-" was used to include studies measuring or collecting data on viewing objects.

The second step of this process was to manually review the 89 articles in a two-stage format: first by examining abstracts for applicability, then by quickly reviewing the full text. We were interested in identifying articles that dealt primarily with measurement along spatial measures (GIS-based approaches) or the effects of greenness exposure (which may have included GIS-based methods). For instance, studies that did not disclose data sources or geoprocessing methods for spatial data were excluded, even if they were conducted in urban areas. Additionally, studies examining psychophysical changes in a small number of participants were excluded despite incorporating spatial datasets. To screen these studies, we primarily focused on their applicability based on the methods section.

After this step, 57 articles remained, which were then subject to a full-text review. In the full-text review, we focused on developing the components of the constructs. The development of the five constructs for UGS measurements and datasets was guided by a structured evaluation of study components.

First, in the data collection section of each study's methods, we assessed three key aspects: (1) the scale at which UGS data were collected, (2) the representation of the data, and (3) how individuals were exposed to UGS. Next, in the study design section, we examined how UGS data were measured and applied, with a focus on (1) whether a Quantitative or Qualitative approach was used, (2) whether data evaluations were Objective or Subjective, and (3) how exposure was assessed. These considerations formed the Methods construct. Finally, the results sections of the reviewed studies informed two additional constructs: (1) Measures, which capture the expected effects of UGS, and (2) Interactions, which describe the nature of engagement with UGS. The organization of these constructs was based on fragmented yet recurring themes in previous studies, which we systematically compiled in the results section.

To refine the constructs, we employed a snowballing method and iteratively identified additional studies that were not captured in the keyword search. This approach allowed us to trace studies with similar research objectives—primarily investigating the relationship between green space exposure and various influencing factors—while also capturing past datasets that illustrate trends in UGS measurement. This process, conducted via Google Scholar, yielded approximately 200 peer-reviewed journal papers, books, conference papers, reports, and technical webpages, which were reviewed with a focus on research objectives and methodologies. Those articles, identified through the snowballing method, were stored in the Zotero reference management software. We categorized the added references according to their respective constructs and compiled a bibliography.

3. Results

The review process identified approximately 200 articles spanning a broad range of disciplines that contributed toward concepts or applications of UGS. Topics covered in this literature include research on health benefits, ecosystem services, urban planning, and the application of remote sensing techniques. Additionally, a focused review of UGS measurements revealed five dominant constructs that guide the field: **scale**, **measures**, **methods**, **green/blue**, **and view type**. These constructs emphasize methodological and measurement-oriented approaches, rather than psychophysical or physiological assessments of exposure to UGS.

Through our synthesis of the literature, we found that the five constructs are commonly considered when collecting UGS datasets. While these constructs are not always explicitly introduced in each study's methods, they frequently emerge as limitations or underlying considerations. For instance, can NDVI-derived greenness datasets fully capture a community's direct experiences and intentional interactions with UGS? Or should subjective data collection be incorporated to better assess UGS at the individual level? These recurring limitations, stemming from the choices made in research design, highlight the need for a more standardized framework. We propose that organizing these constructs across studies serves as an initial step toward defining and standardizing UGS measurements.

The five constructs are commonly applied across three key research fields. First, a significant body of literature focuses on the health benefits associated with UGS [26,50]. These studies demonstrate that exposure to green spaces can lead to improved mental health [70,71], reduced stress [72,73], and better physical health outcomes [74,75]. UGS has been comprehensively linked to lower rates of heart disease, obesity, and mortality, highlighting their critical role in public health [23,76]. Additionally, proximity to green spaces is consistently associated with improved mental health and reduced psychological stress among urban residents [23,77]. Second, UGS is studied in the context of assessment of ecosystem services. These studies emphasize the role of UGS in climate regulation through urban heat island mitigation [78], biodiversity conservation [79], and the management of green infrastructure [80]. Third, UGS data are utilized in the realm of urban and environmental planning. Applications include measured visual impact assessments [61], enhancing the aesthetic aspects of urban environments [40], and landscape planning [81]. Recent advancements in computation technology significantly contribute to this discipline through the integration of artificial intelligence [42] by enabling more sophisticated analysis and applications.

To explore deeper into the application of UGS measurements, Table 2 provides an overview of our five key constructs, offering descriptions and subdivisions of the primary characteristics we identified about UGS in the literature. These constructs –scale, measure, methods, green/blue, and view type- are discussed comprehensively in the following subsections, with a focus on their methodological and measurement-oriented approaches.

Table 2. Constructs of Urban Green Space (scale, measures, methods, green/blue, view type).

Constructs	Characteristics	Description	Citations
Scale	Body/personal scale	The immediate surroundings of an individual (approximately 10 to 100 m)	[36,55,82–84]
	Neighborhood scale	The areas where individuals spend much of their time (up to approximately 500 m)	
	City scale	Used for comparing different administrative jurisdictions	

Table 2. *Cont.*

Constructs	Characteristics	Description	Citations
Measures Effects	Direct effects	The immediate psychological and physiological benefits that individuals experience	[6,85]
	Indirect effects	The broader, long-term benefits of natural environments that contribute to overall well-being	
Measures Interactions	Indirect interactions	Occurring without the need for an individual's physical presence in nature (e.g., video or view through a window)	[6,15,50,86,87]
	Incidental interactions	When individuals are physically present in natural settings, the interaction may be happenstance	
	Intentional interactions	Deliberate experiencing and being with nature (e.g., visiting a park for jogging or a forest for hiking)	
Methods Measuring	Quantitative	The approach measures the amount of UGS (e.g., the proportion of greenness, visible greenness)	[26]
	Qualitative	Using GIS to record individual's preferences (e.g., measuring attractiveness, user's intention to revisit	[88,89]
Methods Data collection	Objective	Includes evaluative indices, such as the amount of green space (e.g., using aerial or satellite imagery, surveys)	[56,90]
	Subjective	Focuses on personal feelings and perspectives (e.g., attachment, accessibility, and impressions of green amenities	[6,91]
Methods Exposure	Availability	The distribution ratio or quantity of UGS in the study area(s)	[6,8,36,38]
	Accessibility	Proximity of UGS to the study location(s)	
	Visibility	Viewable and perceptible UGS at spatial location(s) or linear space (e.g., street)	
Green/Blue	Green Only	Vegetation (e.g., using NDVI as a source data)	[23,80]
	Green and Blue	Vegetation and water features (e.g., pond, lake, ocean, river, waterfall)	
View Type	Perspective	Uses a ground-based (or similar) perspective to conduct assessments	[36,92,93]
	Plan	Uses a top-view approach	

3.1. Scale

Spatial scales represent boundaries that are determined through geographical limits or subjects' perceptual spatial boundaries [26,82,94]. There are a variety of different approaches to defining boundaries. For instance, these can include geographical boundaries using a radial buffer of a site, a network buffer from a home location, or administrative boundaries such as postal codes or districts [95,96]. However, these boundaries and scales may not reflect individuals' psychological boundaries, such as places where residents use spaces for daily activities [84]. Studies aligned with this context, measure the extent of exposure to natural environments or visible green spaces in participants' daily routines

through survey responses [15,41,74,97]. Despite various approaches, the relationship between UGS and individuals remains somewhat unclear, as potential discrepancies may exist between geographical and experiential or psychological boundaries (i.e., what a person perceives or feels within a geographical space, or whether they consciously or subconsciously perceive UGS).

Labib et al. [36] provide three different spatial scales ranging from the individual's cognitive domain to the domain affecting the population level: *body/personal scale*, *neighborhood scale*, and *city/district scale*. These spatial scales are pivotal in geographic analysis because they can influence the selection of units for representing the extent to which greenness affects and is a guide for data collection and analysis in studies of green space [83,98]. The study systematically investigated scales used in empirical studies, categorizing them from micro to macro levels [36]. Body/Personal Scale, also called micro-scale, ranges between 10 and 100 m and focuses on an individual's immediate surroundings, making it highly sensitive to environmental changes [82]. Neighborhood scale is defined by the spaces where an individual spends significant time and regularly interacts with the surrounding environment [26,94,99]. This boundary may be nebulous and ever shifting, yet it could reflect a similar socioeconomic population level. Presently, techniques to define these "fuzzy boundaries" in a GIS can better reflect human perceptions [100–102]. Representations at this scale can be either allocentric (e.g., administrative zones) or egocentric (e.g., buffer distances around a home). City/District scale encompasses a broader area, including all potential spaces used by urban dwellers in their daily activities, offering a more extensive overview of UGS utilization [55,103]. For instance, UGS datasets at this scale are paired with similarly scaled datasets on mortality [103], birth weight [104], and childhood obesity [32] to facilitate comparative analyses among cities.

Each spatial scale serves a distinct purpose, influencing how UGS is measured and how outcomes are interpreted. Understanding the implications of these scales is important for selecting appropriate units of analysis and research approaches.

3.2. Measures

UGS measurements in the reviewed literature fall into two themes: the effects of green space and individuals' interactions with the natural environment.

3.2.1. Effects of Green Space

Experimental studies investigate how UGS impacts subjects by distinguishing between the *direct* and *indirect effects* of the natural environment [85]. For instance, studies hypothesize that varying quantities and qualities of UGS exert discernible effects on individuals or residents [90]. These studies posit that different levels of exposure to UGS can lead to varied outcomes, either positive or negative [8].

Direct effects focus on how individuals perceive or use green space, and they are closely tied to the approaches used for measuring these spaces. For instance, studies measuring the direct effects of green spaces focus on designated areas where positive changes can be immediately observed [105]. In contrast, the indirect effects involve assessing the UGS impact on a broader, unspecified population, typically within a buffer zone of distance that may affect nearby residents [95]. Although not all experimental studies explicitly distinguish between the direct and indirect effects of greenness, these two characteristics often influence the location and size of the UGSs to be measured [33,95,106]. Direct effects are often examined in psychological and physiological studies, referring to the immediate benefits that individuals experience when exposed to natural environments. These effects are tangible and observable, often measured through changes in emotional and physical states [107]. For instance, viewing greenness through windows

requires measuring only a limited space of green areas [108,109]. Additionally, walking in a park [110], urban forest [105], street [111], or other natural settings involves measuring the exposure to greenness as participants move through the study area [112]. Such studies focus on whether perceivable greenness brings about psychological restoration or changes participants' mental fatigue by reducing it.

Indirect effects, on the other hand, involve broader, cumulative benefits from perceived natural environments [107]. These effects reflect the present status depending on the measured environments in certain periods, using cross-sectional designs in health-related studies. For instance, Maas et al. (2006) [18] used the total percentage of green space to explore the association between distributed vegetation and perceived general health. Approaches to measuring the indirect effects of existing green space often align with theories of cognitive restoration, measures of general well-being, and mitigating stressors of urbanization [6]. Besides, enhanced accuracy and capacity of UGS data processes have contributed to large-scale epidemiological studies, particularly at the national level [55,113].

3.2.2. Interactions with UGS

Keniger et al. [86] proposed a framework that defines three types of interactions (with the natural element of the environment): indirect, incidental, and intentional types. This framework classifies the extent to which green space is physically present in an individual. While few studies explicitly identify this distinction, the framework provides a structure for understanding how different types of interaction can clarify the relationship between health benefits and the residents in the study area.

Indirect interactions occur without physical presence, such as looking at nature through a window. For example, watching an urban park through the window in the office room or a forest of mountain areas is included in this interaction. Indirect interaction even encompasses green spaces through media so, the studies that examine the laboratory with devices (e.g., television screens, virtual reality) also belong to this type. Indirect interaction also includes viewing green spaces that are inaccessible, such as scenery observed from a building [109] or while in a moving vehicle [92]. Regarding UGS datasets, several studies have focused on sequentially viewing scenery [44] or tracking long-term changes in landscapes [114]. Studies assessing the visibility of UGS to unspecified individuals may implicitly rely on the premise that such interactions take place.

Incidental interactions happen when a person is exposed to green space through an unplanned outcome. For instance, a person's commute may provide a certain degree of green space exposure, despite that person not directly planning the route to engage with the green space. Likewise, a walk from the home to a school may provide incidental interaction [115]. A large body of visibility analyses represent these interactions, whereby they assume effects stem from views of green spaces as the predominate form of exposure. Moreover, studies investigating the benefits of nature using available UGS datasets are likely to account for these incidental interactions. This is because UGS datasets representing availability typically focus on accessible spaces, such as public parks or green spaces located near sidewalks [25].

Intentional interactions require purposeful visiting of green space. The key distinction of these interactions lies in the deliberate intention to experience nature, requiring studies to acknowledge participants' purposeful behavior. This could involve doing an activity within a green space and selecting an activity that maximizes green space exposure, such as gardening, hiking, or picnicking in a park [43]. Research on intentional interactions often necessitates additional user data (e.g., GPS tracking), which can be applied to GIS-based map datasets [87] to explore the relationship between UGS and health benefits.

3.3. Methods

In this section, we explore three different methodological themes identified in the literature. These themes include measurement approaches, methods for data collection, and finally, how researchers are producing exposure assessments. Figure 2 illustrates these three themes (Measure, Data Collection, and Exposure assessment), along with the associated subtopics, which are further explained below.

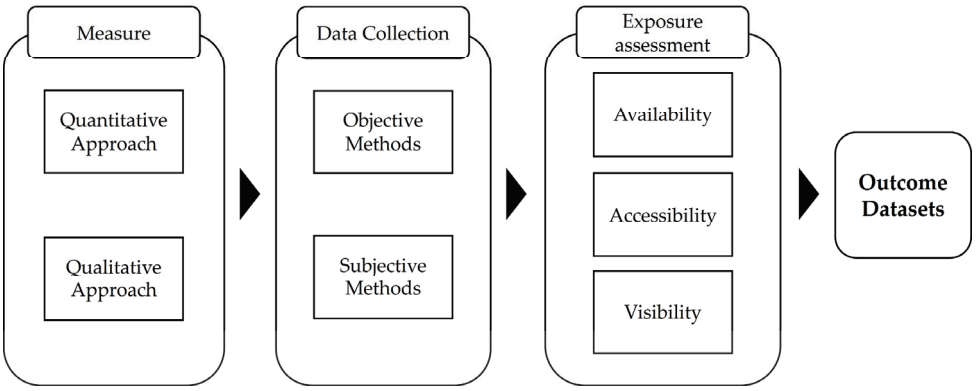


Figure 2. Conceptual diagram of UGS data collection method design. This diagram outlines the internal decision-making processes essential for designing UGS data collection methods. These considerations help researchers anticipate the data's impact on dependent variables within UGS studies.

3.3.1. Quantitative and Qualitative Measures

As with many fundamental research methods, there is often debate over the use of quantitative and qualitative approaches, and UGS studies are no exception. A variety of studies collect UGS data through remote sensing to quantify greenness, typically using these data as variables in statistical analysis (e.g., how much green in each boundary), characterized by their value (density, how green, or how vigorous the growth) and location (boundary). Interestingly, the processes for data collection and the variations of these sources allow for flexibility in how UGS data can be used, both in quantitative and qualitative ways. Quantitative measures primarily focus on the extent of UGS, such as the area occupied by green space, the proportion of tree canopy, and the amount of visibility of greenness along streets [116].

In contrast, qualitative measures emphasize the characteristics that influence UGS performance related to perceived and experienced nature [117]. These assessments mostly involve surveys that evaluate the attractiveness of green spaces using quality audit tools, accessibility [118], or other quality aspects like visual landscape, aesthetic appeal of large gardens, and facility quality for epidemiological studies [119–121]. Despite the predominance of quantitative approaches, the complexities in defining UGS quality may explain the limited empirical research on its health effects [58,89]. Assessing UGS quality can be challenging due to its subjective nature, which is often reliant on individual preferences [122,123]. Due to the limitations of qualitative measures, studies increasingly rely on quantitative data to examine the relationship between residents and green spaces, aiming to provide a more structured understanding of UGS influence.

Although there is no universally accepted definition of UGS quality, some studies integrate qualitative measures with evaluations of ecosystem services, such as species richness and land cover diversity [81]. UGS quality assessment often also employs qualitative measures to evaluate landscape aesthetics and mental health impacts. For instance, Swetnam et al. [121] highlighted the integration of perceptual surveys with visual quality indices to capture the aesthetic values of landscapes, recognizing the significance of individual experiences in UGS evaluation. Similarly, Hermes et al. [81] utilized commu-

nity feedback to assess landscape features like naturalness and uniqueness, providing a broader understanding of UGS quality from a public perspective. Bratman et al. [4] discuss the mental health benefits derived from natural settings, emphasizing the necessity of qualitative insights to fully appreciate the therapeutic potential of UGS. These approaches underscore the importance of qualitative measures in capturing the impacts of UGS through quantitative measures on human well-being.

3.3.2. Objective and Subjective Methods

Objective and subjective methods are the foundational approaches in UGS data collection, each diverging significantly during the data collection process. Objective methods strive for unbiased and unintrusive measures of greenness. Quantitative remote sensing data are commonly used in these methods. For instance, the Normalized Difference Vegetation Index (NDVI), Land Use/Land Cover (LULC), and imagery from Google or Baidu Street View are sometimes used as key datasets for objective methods. NDVI is extensively employed to quantify vegetative greenness, measuring areas of vegetative growth that can then be compared across neighborhoods or districts [104,124]. Additionally, NDVI can be coupled with viewshed analyses to represent how much of the vegetation might be visible from the ground level. LULC datasets are a unique product of satellite imagery that has been classified into specific land cover types. A number of these products exist and can provide the classification of the difference between grass, as well as deciduous and coniferous trees (as well as a host of other values). Some data are used to distinguish between urban forests and open parks. This offers a distinct advantage for identifying different kinds of use-cases for green space in urban settings [13,125,126]. However, those datasets need additional analysis to represent more complicated experiences of UGS, such as accessibility or visibility of UGS [127].

Unlike remote sensing (or other imagery captured from aircraft) that captures imagery from above, Street View images provide objective data but from a perspective view. These 360-degree images are increasingly used to measure eye-level urban greenness [128] taken by vehicle-mounted devices, showing what structures or vegetation are visible to individuals on the road. Early methods used Adobe Photoshop to extract green pixels from digital photographs [129] but advances in data handling and algorithmic processing have evolved these methods. Modern approaches use machine learning technology for advanced image segmentation. This technology identifies different types of vegetation, enhancing the scope and accuracy of UGS measurement [44,130].

In contrast, subjective methods prioritize perceived green space, capturing individual experiences and behaviors associated with UGS [131]. These methods explore the qualitative dimensions of urban greenery, emphasizing personal or communal impacts [122]. Common techniques include surveys and interviews [35,132], which explore the green spaces encountered by research participants. For example, Jiang et al. [41] conducted an online survey to assess participants' frequently used routes, measuring the visibility of greenness along these routes as indicators of green space quality.

Subjective assessments often involve direct inquiries into various aspects of green space quality, such as park availability [120], management [122], and visual impression [114]. In research on topics such as visual landscape assessment and when trying to gather empirical data about how people engage with cultural ecosystem services, subjective methods are indispensable. They inherently rely on cognitive paradigms [91,133] that require individuals to assess their use of values and interpret that into some quantitative value or through a story that can later be interpreted by researchers. In many cases, individuals are asked to interpret data using scales (e.g., Likert scales [134]), to evaluate factors like tree cover density [112] or landscape aesthetic potential [135].

3.3.3. Exposure Methods

The measurement of exposure to UGS can use a range of different qualitative and quantitative approaches, as well as incorporate both objective and subjective methods [23,36]. These types of assessments serve as a bridge between how something is measured and how it might be used or experienced [26]. A broad range of studies in urban planning and public health disciplines explore these approaches. Their purpose is typically to link UGS to the quality of the living environment and overall public health [8,56]. One of the seminal studies cited in this review by Labib et al. [36] introduced three different types of exposure methods: *availability*, *accessibility*, and *visibility*.

The availability assessment is most often represented as an amount of greenery. Studies consistently demonstrate that the availability of green space contributes to improved mental health outcomes, reduces heat island effects, and enhances biodiversity [23,76]. The NDVI and LULC datasets are frequently used to objectively measure vegetative cover, providing the amount of greenery and the relationship with general health in the study areas [8,18]. Additionally, the distribution of availability reflects socioeconomic disparities, impacting lower-income neighborhoods with limited green space availability [32]. This inequity suggests that increasing green space availability could be a crucial intervention in reducing health disparities [52].

The accessibility assessment refers to the ease with which urban residents can access (or get to) green spaces. Usually, this refers to a proximity measure. Research indicates that proximity to green space significantly impacts physical activity levels, mental health, and social cohesion [56,124]. For example, proximity to parks and recreational areas has been linked with increased physical activity, which can mitigate chronic diseases, such as obesity and diabetes [27]. By measuring the accessibility of UGS, studies identified mental health benefits [8,23], and encouraging physical activity [73].

Visibility assessments aim to quantify the extent of visible vegetation or greenness. These approaches focus on what is directly visible to individuals in their immediate environment. This assessment fundamentally relies on data collected from an individual's eye-level perspective, often referred to as the perspective or profile view. Unlike the previous two types of assessments, visibility assessments employ a distinct technique [36], which may include viewshed-based analyses or image interpretation methods (e.g., Green View Index).

Data from visibility assessments are utilized for various purposes including the visual impact assessment of landscapes [69], alleviating mental fatigue, and enhancing mood stability [136], as well as evaluating urban landscapes on a large scale [42]. Specifically, GIS-based visibility analysis has been instrumental in assessing changes in suburban landscapes [92,137]. Recently, these analyses have expanded into urban areas, driven by increased computational capacity and the availability of rich datasets [38,136,138]. Moreover, advances in image interpretation techniques over the past decade have also been spurred by the data provided by major technology companies (e.g., Google, Baidu, etc.). For instance, the Green View Index now effectively distinguishes greenness in captured images [128], while machine learning models based on deep neural networks have started to identify preferences in urban landscapes by analyzing street structures [42, 44]. Consequently, the scope of visibility assessments is broadening, intersecting with disciplines such as psychology, ecology, and urban planning, thereby enriching the metrics used in urban analysis [38,69].

3.4. Green and Blue

The typical interpretation of UGS focuses on vegetation (green) elements. However, there has been an emergence of research lumping blue features into the same discussion [23]. Where green features encompass a range of elements from grass to forest, blue features incorporate elements such as rivers and the ocean. Thus, when measuring UGS, it is important to identify if both blue and green features are included, and in which way (e.g., do they share the same value).

The distinction between green and blue can be very apparent. For instance, studies using the NDVI often exclude water features to focus on activities that are directly related to health benefits [139], even though blue features can be directly used for health benefits [126]. In contrast, we identified studies that used land use datasets that included water features, as elements like ponds in parks or rivers in waterfront recreation areas. From an ecosystem services perspective, researchers have identified that blue and green features can be used to increase the provision of cultural services [140]. It is well known that water features enhance the aesthetic and recreational value of urban landscapes and contribute significantly to urban biodiversity and microclimate regulation [141,142]. Their presence has been linked to increased property values and improved mental well-being among residents, illustrating the multifaceted benefits of integrating blue spaces in urban planning [143]—benefits that are similar to UGS.

There are multiple other benefits of blue features that make it important for consideration in studies involving nature. For instance, the visibility of water bodies, as discussed by Nutsford et al. [126], is associated with significant mental health benefits, including reduced stress and improved mood stability. This underscores the importance of not only the physical but also the visual access to water features in urban settings. Research by Labib et al. [36] supports this, demonstrating that the eye-level visibility of green and blue spaces significantly influences residents' psychological well-being [23]. The strategic integration of green and blue spaces has been shown to mitigate urban heat island effects and provide essential refuges for urban wildlife, thereby enhancing the sustainability and livability of cities [80]. Studies further highlight the importance of incorporating both green and blue spaces into urban environments to fully capture their benefits for urban residents [30,37]. While water features may sometimes be excluded when assessing the specific impacts of green spaces on individuals, their significance in the broader urban context is increasingly recognized due to their critical roles [36].

3.5. View Type

This construct focuses on representing UGS in two distinct ways: (1) *perspective view* and (2) *plan view* (Table 2). The perspective view (sometimes also referred to as 'profile view') is conducted at ground level, offering a view from the individual's perspective [61,92]. Studies may use the perspective view to represent direct human viewing (and subsequently psychological perspective). Conversely, the plan view typically employs a top-down approach, such as birds-eye or satellite imagery [36]. A key distinction between these techniques lies in the outcomes, which reflect different extents of experiential greenness and assumptions of the way individuals are exposed. They also tend to be based on different data sources. Empirical studies have shown these two views demonstrate weak positive correlations when representing the greenness of a study area [54,93,128]. Therefore, some studies collect data from both perspective and plan view to analyze their effects on residents' perceptions and experiences of UGS [43].

The perspective view differs from the plan view, where the latter is typically driven using geographic information data (e.g., satellite imagery or vector-based representation of urban elements). While datasets derived from plan views have been widely used in various

studies due to their immediate applicability from remotely sensed raw data, the use of perspective-view datasets has also gradually increased in recent decades. It is important to note, that Ekmen and Kocaman [144] argued that remote sensing approaches in urban areas may disproportionately represent studies about UGS, but the subjective interpretations and qualitative methods may not be as well represented—but still carry valuable knowledge. Moreover, Zhu, Zhou, Seto, et al. [57] emphasize the need for collaboration between remote sensing leaders and policy-making to ensure data applicability. Addressing these oversights requires a thorough examination of current measurement techniques and the development of a conceptual framework that fosters mutual understanding between method developers and data users.

Here we emphasize the view types construct as this is frequently discussed in the literature. View types offer a means to represent and discuss how the other constructs are folded together. Table 3 summarizes key methods, data, and outcomes that are associated with these view types. These are further explored in the following subsections.

Table 3. Classification of View Type construct into techniques, geospatial data, and outcomes associated with UGS.

View Type	Technique	Methods	Geodata for Analysis	Outcome Data Description	Citations
Perspective View	Viewshed	Viewshed	TIN model, LULC	Landscape composition	[114]
			DEM, NDVI	Visibility maps of greenery	[25]
		Visual Magnitude	LiDAR-derived surface height model	Mapping the perceivable greenness on the urban trails	[145]
			DTM, DSM, LULC	Measuring visibility of transmission lines (visual impact assessment of green area)	[61]
			DEM, Wildlife Tree Patches	Visibility analysis for scenic areas of forest	[146]
		Vertical Visibility Index	DEM, LULC	Conversion of green space visibility to an ordinal score	[126,147]
		Visual Exposure	DSM, Tree Canopy data, Geographical Boundary of city	Mapping eye-level greenness visibility exposure	[136]
				Mapping green visual exposure to individuals	[106]
	GVI	GVI	SVIs, Coordinated map of image locations	The ratio of the total green area in street view images	[45,93, 128]
		GVI with AI		Interpretation of vegetation ratio in SVI images	[44]

Table 3. *Cont.*

View Type	Technique	Methods	Geodata for Analysis	Outcome Data Description	Citations
Plan View	Multi-Spectral Remote Sensing	NDVI measurement	CIR photography from satellite or uncrewed aerial vehicles.	The ratio of total vegetation area in each study area	[77,115, 148]
		LULC measurement	The Anderson land cover classification system, Decision Tree Algorithms (e.g., LANDSAT, NLCD, and LGN)	Measuring the ratio of parks and the forests or the percent of green space (trees, shrub, and grass-herbs)	[18,32,96, 148]
				Measuring the proportional abundance of vegetative cover (i.e., forest, shrubland, and herbaceous)	[53]
		Tree canopy measurement	Photo interpretation of multi-spectral imagery and other ground and ancillary information	Calculating the average or percentage of tree canopy cover within the defined administrative boundaries	[17,55, 149]
	Other	GPS tracking of users	Location (e.g., GPS device or smartphone)	Measuring the activity spaces where exposure to green space occurs	[87,150]

Definitions: AI: Artificial Intelligence; CIR: Color Infrared; DEM: Digital Elevation Model; DSM: Digital Surface Model; DTM: Digital Terrain Model; GVI: Green View Index; LGN: Land Use Database of the Netherlands; LULC: Land Use Land Cover; NLCD: The US Geological Survey National Land Cover Database; SVI: Street View Image; TIN: Triangulated Irregular Network.

3.5.1. Perspective View

The perspective view approach involves various methods typically derived from variations of a GIS-based viewshed algorithm [38,92,106,136,147], but includes a fundamentally distinct approach called the *Green View Index* (discussed at the end of this section). Viewshed approaches are usually based on geospatial datasets, such as NDVI, LULC, and Tree Canopy Cover datasets together with topography data (and other visual constraints). These analyses identify the amount of green space that might be visible from a given location or route. The second technique, known as the Green View Index, quantifies visibility by analyzing large collections of geo-tagged photographs. This process identifies the amount of green within a photograph. The various techniques are highlighted in bold italic text in the following paragraphs.

Viewshed analysis is a key technique used to determine the visibility of objects or areas from specific viewpoints [151,152]. An early concept was developed by Tandy [153] as a line-of-sight (what can be seen from a place) known as an "isovist" [154]. With the advent of topography data (e.g., Digital Elevation Model or Triangulated Irregular Network) and GIS-based computer applications viewsheds have become popular. They have been used to identify historic sites [155], estimate the visual impact of landscapes [61], and evaluate the conservation of scenic views [156]. These have been studied in a range of different disciplines (i.e., archaeology, natural resources, urban planning, and computational) due to the ease of tool access through GIS applications [38]. Viewshed analysis is an umbrella term for several specific kinds of implementations (e.g., viewshed, isovist, voxel, visualscape, etc.). There are also advanced versions, including VIEWIT [157], Visual Magnitude [92],

and the Viewshed Greenness Visibility Index [136]. These developments highlight the adaptability and expanding scope of viewshed analysis.

Viewshed analysis quantifies areas as visible or invisible and is commonly used to assess viewing landscapes at designated points. Previously, calculating visibility for numerous viewpoints on a large scale, such as metropolitan regions, posed computational challenges. However, advancements in processing power now enable the handling of visibility calculations for millions of viewpoints [136,158]. For example, during the early period when GIS applications began including viewshed modeling as one of their functions, Palmer [114] employed a viewshed to analyze changes in landscape composition across a township, employing 56 viewpoints with a 30 m resolution DEM. More recent studies have expanded this approach to city scales. For example, Nutsford et al. [126] utilized 46 viewpoints with a 5 m resolution over four distance ranges (i.e., below 300 m, 300 m to 3 km, 3–6 km, and 6–15 km). Additionally, Laszkiewicz and Sikorska [25] assessed the visibility of greenness along children's school commute routes by analyzing data at 10-m intervals across 73,376 points in an urban area. These studies illustrate that the visibility of specific features or greenness can be quantified across entire cities. Furthermore, the visibility data can be integrated with other urban datasets, such as health or socioeconomic data, to explore complex environmental and social relationships within urban contexts.

The viewshed analysis delineates areas visible from selected points on a map [151,159]. By overlaying vegetation or tree canopy data onto the viewshed results, one can approximate the extent of visible greenness from the points. Visible greenness data from the viewshed differs from NDVI measurements, which are conducted through a plan view and show the existing green space on the ground. However, some studies have noted that existing green space on the ground and visible greenness derived from image analysis do not correlate as the measurement area radius increases [93,128]. Although measuring visible greenness through images utilizes a different approach, there are common reasons why the visibility of greenness and actual greenness might differ, particularly in terms of perceivable green space. For example, private gardens or small parks nestled between buildings may not be visible to pedestrians unless they move to see those spaces, yet the data from the plan view include those as existing green space [136]. Furthermore, urban structures such as highway overpasses, high-rise buildings, and other physical barriers often obstruct views of green spaces. Thus, often, some communities have proximity to large green spaces but are neither accessible nor visible.

The viewshed analysis has evolved over the years to include other variations, which include *visual magnitude*, *vertical visibility index*, and *visual exposure*. These enhanced approaches shift away from the binary representation of viewshed analysis (to see or not to see) to account for a more continuous representation of visibility [92]. One development in this field is the introduction of visual magnitude which computes the portion of visible area within an observer's sight, factoring in topographical elements including slope, angle, and observer-relative distance [152,157]. Visual magnitude quantifies the extent of visible areas within an observer's view, with values ranging from 0 (not visible) to 1 (fully visible). A related analysis, "Cumulative Viewsheds" incorporates the frequency with which areas are seen from different viewpoints. One of the earliest implementations of this work was produced in the program "VIEWIT" [157,160]. Numerous other methodologies have been applied to represent a more human-centric visibility measurement, such as fuzzy analysis [161], vertical visual angles [152], and route-based visual magnitude [92].

Many studies from the literature focus on visual magnitude methods to assess the visual dominance of specific objects within landscapes. Wilson et al. [145] utilized visual magnitude to analyze the visual characteristics of urban trails, with a focus on aspects such as visual openness and perceived greenness from the observer's eye level while

walking. Other studies, including those by Chamberlain et al. [146] and Palmer [61], used visual magnitude to quantify the visibility of undesirable objects, such as logging areas and transmission towers. These studies not only measured the extent to which the negative visual impacts of these objects could be mitigated but also provided a quantitative assessment of visibility based on observer location, including Key Observation Points and route-based viewpoints. Although these studies do not directly focus on UGSs, they offer important examples of how visibility measurements can be applied to minimize negative visual impacts on landscapes.

We also identified another approach called the vertical visibility index as one of the viewshed extension methods. This approach calculates visibility by assessing vertical angles and distances from each observer point, effectively representing the visibility of greenness from a vertical perspective [147]. In validating this method within an urban context, a significant positive correlation was found between Vertical Visibility Index scores and the visibility verified through Google Street View imagery. This method was employed to measure residents' exposure to green and blue spaces, which was associated with psychological distress and other socioeconomic factors [126]. The study integrated elevation models with land cover data to assess the visibility of green and blue spaces across four distance spectrums. Notably, this research measured the visibility of green space in an urban setting and explored the relationship between viewing natural landscapes and the mental health of participants.

Visual exposure and visual magnitude share similarities in their measure, but visual exposure also attempts to account for the density of green visible. This can require a higher resolution of data to process or supplemental data to determine how to quantify density. In our review, only a few previous works applied visual exposure to quantify visible UGS. Here, we identify two recent studies based on the technique and developed innovation models: (1) the Viewshed Greenness Visibility Index and (2) green visual exposure. The Viewshed Greenness Visibility Index was developed by Labib et al. [136]. This technique reduces computational complexity through the filtering process and increases the accuracy of the green space visibility through the necessary parameters (i.e., distance decay of visibility). The Viewshed Greenness Visibility Index used digital terrain models and LULC to identify UGS, calculating approximately 86 million observation points in a metropolitan area in the UK. The second technique developed by Cimburova and Blumentrath [106], incorporates existing viewshed extensions such as visual magnitude [92], solid angles [162], and the distance decay function [136]. Their approach is based on the reverse-viewshed that the number of visual objects (e.g., street trees) is fewer than the number of potential observation points. For example, while trees can be seen from numerous locations, the actual number of trees or tree groups in an urban environment is less than the number of observation points. This approach reduced the time for calculations so, they could analyze the visibility of urban trees in Oslo, Norway. These studies demonstrate that visual exposure, assessed through viewshed-based visibility analysis, is a feasible method for utilizing high-resolution datasets at the city scale.

An alternative to viewshed-based analyses is the green view index. Measures the proportion of greenness in an image or photograph taken at a specific location. This method has gained widespread use as a variable representing green space visibility, especially with the accessibility of street view images provided by platforms like Google, Baidu, and OpenStreetMap. Initially developed by Aoki et al. [163], the Green View Index involved manually counting vegetation pixels in images, which later became automated with digital tools like Adobe Photoshop [129]. As computer programs evolved, Green View Index calculations could be scaled to entire cities, making it a valuable variable in epidemiological studies. Green View Index, constructed from a perspective view of images, effectively represents

the visibility of green spaces from the observer's viewpoint. Its prominence has grown due to the abundance of street view data and advancements in automated processing.

In recent years, artificial intelligence has further enhanced the accuracy of street-view image interpretation. For example, Zhang and Hu [44] used artificial intelligence to improve the Green View Index by distinguishing street trees and ground vegetation through semantic segmentation—a computer vision technique that categorizes groups of pixels. Notably, their study calculated the Green View Index for the entire city of Osaka, Japan, using a large dataset of street view images and artificial intelligence models trained with the Cityscapes Dataset [164] and Objects Contextual Representation model for pixel classification [165]. Like other Green View Index studies, this research integrated the index into GIS-based maps, creating two types: one showing greenness at image locations and another depicting the average Green View Index for road segments.

3.5.2. Plan View

The plan view is a top-down approach that aims to calculate UGS from above, typically with less focus on measuring how people view green space as in the perspective view. For several decades, green space data derived from satellite or aerial imagery have been considered effective for research and planning, particularly due to their broad coverage at city and regional scales [8,51]. These data represent the distribution of vegetation to derive a UGS exposure. In this subsection, we identify four different approaches to assessing UGS from the plan view, including remote sensing approaches such as NDVI, LULC, Tree Canopy, and another variation that combines existing data (remote sensing or vector-based data) but focuses on exposure by directly tracking individual movement. As in the previous section, each of these techniques is highlighted in bold italic font.

The Normalized Difference Vegetation Index (NDVI) is one of the most commonly and frequently used metrics for measuring UGS [8,77,148,166]. NDVI is calculated by determining the ratio of red and near-infrared bands using multispectral imagery captured by multispectral cameras [167]. Although recent studies have employed various approaches to measuring UGS through multispectral imagery—such as the Enhanced Vegetation Index, which is more responsive to tree canopy structure [166], and the Soil Adjusted Vegetation Index, which can suppress soil pixels [139]—NDVI remains a consistently used method due to its popularity [23,51]. Since many other indices are derived from NDVI, this review focuses on the application of NDVI and current trends in its usage.

The resulting geospatial data are, generally, published in raster format, which are ortho-mapping products classified into plan view datasets. Most studies we found collect the proportion of greenness or vegetation areas from satellite imagery, such as Landsat 5 [77,93,148], WorldView-2 [90], and Sentinel-2 [136]. NDVI effectively distinguishes areas covered with healthy vegetation from non-vegetated areas, such as concrete or bare land, because the calculation is designed to be sensitive to chlorophyll content. As a result, studies using NDVI should consider seasonal effects, ensuring that imagery captured during the growing season is used to measure UGS accurately. Additionally, selecting cloud-free imagery [115] and excluding areas with rivers or reservoirs, due to the presence of aquatic plants that also contain chlorophyll [139], are critical factors in accurately gauging greenness, which directly affects residents.

In recent studies, imagery captured via uncrewed aerial vehicles has emerged as a promising alternative to satellite imagery. Several studies have validated that NDVI derived from satellite imagery corresponds well with NDVI from uncrewed aerial vehicle imagery equipped with multispectral sensors [168,169]. Moreover, Uncrewed Aerial Vehicles can overcome limitations inherent in satellite-based approaches. For instance, satellites can only capture a region when their orbit passes directly overhead, whereas

uncrewed aerial vehicles offer greater temporal flexibility, as long as they can fly over the area [170]. Additionally, uncrewed aerial vehicle imagery provides high spatial resolution and is relatively low-cost compared to traditional aerial photography captured by airplanes, making it a viable alternative to current satellite image capture methods. Lastly, uncrewed aerial vehicle-based remote sensing is particularly suitable for smaller scales, such as city management, a point increasingly emphasized in studies focused on measuring urban environments [169,171].

Land Use and Land Cover (LULC) data are extensively utilized to quantify and characterize specific aspects of the built environment [8]. Numerous studies focusing on UGS use these datasets to identify areas such as parks [32], urban forests [125,148], or non-agricultural vegetated areas [18,172]. Additionally, LULC data within urban contexts are employed to analyze ecosystem services, sustainability, and urban sprawl, enabling the creation of comprehensive models [5,27,173]. A key distinction between LULC data and the NDVI lies in their creation: LULC data are derived from classification systems (e.g., The Anderson land cover classification system) and processes [174], while NDVI is calculated using an algebraic formula [175].

LULC datasets are widely utilized as geospatial maps [176]. Land use data represent functions of land, such as recreational areas or residential zones, whereas Land Cover datasets depict the land's physical attributes, including water bodies, forests, and wetlands. For instance, in the United States, the National Land Cover Database provides detailed land cover information, while the Major Land Uses dataset from the Economic Research Service captures socioeconomic changes and landscape alterations driven by human activity [177]. Similarly, datasets like the Urban Atlas from the European Union's space program [178] and the National Land Use Database from the Netherlands (LGN) offer multiple layers of information under the combined category of Land Use and Land Cover [18,179].

Although both LULC and NDVI data utilize a plan view to represent UGS, they serve distinct yet complementary purposes in analysis. LULC data categorizes land use and cover types, while NDVI provides insights into vegetation health and density. Their combined use offers a more comprehensive understanding of green spaces. For instance, Dennis et al. [117] quantified various types of green spaces using LULC data, while NDVI was employed as a quality metric for assessing vegetation health. Similarly, Yin [148] used NDVI to measure overall greenness and LULC data to estimate tree canopy coverage, providing detailed insights into the extent and types of green spaces across different buffer zones. Consequently, researchers and planners must have a clear understanding of how to effectively use LULC data in UGS measurement, along with a well-defined process for classifying vegetation types, to ensure accurate and relevant analysis.

Tree Canopy Cover (TCC) refers to the area covered by trees when viewed from a plan view and is increasingly used in various UGS measurements. These data provide information on the proportion of tree canopy that urban residents can visually perceive [106] and is used to assess the overall quality of UGS, as it contributes to the ecosystem services of urban areas [180]. Although often a byproduct of LULC data analysis—such as data derived from the classification of high-resolution satellite imagery, for example, Foliage Projection Cover from SPOT 5 [180], Tree Canopy Cover from Landsat [77], and City of Trees from Copernicus Sentinel [117]—Tree Canopy Cover is considered to have unique characteristics in UGS measurements, unlike NDVI and LULC.

We reviewed studies that applied Tree Canopy Cover data as a factor in UGS measurement. In epidemiological studies, Tree Canopy Cover represents the percentage of tree canopy coverage in different neighborhoods and is used to evaluate vegetation quality through complex models, such as green infrastructure calculations [117], assessments of street tree influence on health perceptions [17], and air pollution reduction measurements

using the U.S. EPA Environmental Benefits Mapping and Analysis Program model [149]. These studies indicate that Tree Canopy Cover data are often used to provide a more precise representation of greenery that directly impacts urban residents through managed vegetation. Conversely, other studies have used Tree Canopy Cover data as a variable to account for household characteristics [180,181] and city-level health outcomes [55]. For example, in Lowry's [181] study, the influence of built environment and socioeconomic factors on neighborhood tree canopy was analyzed using high-resolution (1-m resolution) data from aerial color-infrared digital imagery, such as from the National Agriculture Imagery Program.

Tree Canopy Cover data in UGS measurements is frequently integrated into green infrastructure assessments due to its specific resource-related characteristics [182]. In urban contexts, trees require ongoing management and resources to thrive. Additionally, as an infrastructure element that provides direct benefits, tree canopy can represent shaded areas or rest spaces in impervious, developed areas. For instance, several studies have used Tree Canopy Cover data to explore the relationship between sun exposure and skin health [183]. Therefore, as this dataset increasingly improves in accuracy, it becomes a critical indicator of environmental quality in residential areas, directly offering benefits tied to investments in natural resources.

One downfall of plan view techniques is their assumption of how individuals are exposed to UGS. Some work has overcome this limitation by employing GPS tracking of UGS. This allows for precise analysis of individuals' movements about green spaces [87,99,150]. Recent studies have shown that combining GPS tracking with GIS data improves the measurement of environmental exposures by capturing daily mobility patterns and providing a more comprehensive analysis of interactions with urban environments [99]. These datasets typically include information on the frequency of visits to green spaces and the duration of time spent there, providing a practical understanding of user behavior and engagement with UGS. Chaix et al. [99] claimed that GPS data allows for an assessment of environmental exposure, moving beyond static residential data to include detailed daily mobility patterns. Further, Marquet et al. [87] found that increased greenness within GPS-defined activity spaces positively correlates with higher physical activity levels, emphasizing the health benefits of regular exposure to green spaces. Additionally, Zhou et al. [150] further highlighted that GPS data can capture both the frequency and duration of visits to green spaces, offering a deeper understanding of how environmental perceptions, such as park safety and beauty, influence park usage.

Future research directions suggest various integrations of GPS data into GIS systems to not only map patterns of users but also contextualize environmental and health-related data. In the review by Chaix et al. [99], they advocate for more studies that explore how these datasets can be used to assess long-term health impacts. On the other hand, in the experimental study by Marquet et al. [87], they propose linking GPS data with health interventions and urban planning strategies to create more sustainable and walkable cities. Similarly, Zhou et al. [150] call for integrating temporal variations in GPS-tracked park usage with perceptions of safety and beauty to inform the development of UGSs. Consequently, the reviewed studies emphasize the need to store data consistently using GPS devices and to integrate such datasets with other geospatial datasets to better analyze relationships between these datasets.

4. Discussion

4.1. Defining Urban Green Space: Challenges and Approaches in Current Research

Defining UGS through a set of uniform criteria remains a challenging task. Most studies reviewed in this study treat UGS as a variable, collecting the datasets depending on

their study areas that are typically urbanized with high populations [35,55,71,77,104,113]. Complexity arises from the diverse functions and perceptions of UGS, making it difficult to establish standardized definitions [12,184]. For example, when grouping UGS by function, if all vegetation areas measured by the NDVI are classified as UGS, questions emerge about whether private lands or inaccessible urban forests should be included.

Beyond these function-based classifications, a wide range of disciplinary perspectives could further enhance a construct-based definition of UGS. For instance, ecosystem services approaches evaluate UGS based on the benefits it provides, such as mitigating urban heat islands, improving air quality, supporting biodiversity, and others. Economic valuation methods, such as hedonic pricing and contingent valuation methods, assess UGS by quantifying its financial impacts, including how green spaces influence property values, consumer preferences, and cost–benefit trade-offs in urban planning. Civil and environmental engineering may take an infrastructure perspective and focus on aspects like stormwater management and noise mitigation. Psychological and perceptual frameworks expand the definition of subjective experiences and interactions. While some of these approaches align with the construct-based framework presented in this paper, our approach could be expanded further, reinforcing the idea that UGS is best defined through constructs rather than a singular, fixed definition [12].

While these perspectives offer valuable insights, they are often structured around predefined benefits or functional roles of UGS rather than explicitly addressing the variability in how UGS is or could be defined and measured. For example, the Ecosystem Services framework assesses UGS based on its ecological and social contributions which could be measured and assessed in a variety of ways. Similarly, the Green Infrastructure framework integrates UGS into broader sustainability and planning strategies, which typically focus more on outcomes or effects. In contrast, our construct-based framework provides a systematic classification scheme that does not assume a predefined set of functions of purpose but instead enables researchers to define UGS explicitly through scales, methods, measures, and exposure types relevant to their specific study contexts. This adaptability allows for greater comparability across studies or policies by helping to define how an outcome or benefit might be explicit. Therefore, the construct-based approach can address implicit assumptions in UGS-related research.

Here, we discuss two example studies to illustrate how the construct approach can be implemented (Table 4). For example, Wolch et al. [32] assessed the impact of adjacent parks in a residential area. Their spatial analysis focused on neighborhood scales in communities in Southern California, U.S. The relevant categories under measures include direct effects and intentional interactions. Regarding methods, the study analyzed distance to parks within 500 to 1000 m radii buffers to compare obesity rates among communities. The study employed a quantitative approach to measure UGS areas and objective data collection of the built environment. Moreover, the dominant exposure to green space was classified as accessibility of UGS from participants' residential areas. The study included ponds in its park distribution dataset, reflecting the inclusion of water bodies (blue-space) as part of UGS. Lastly, a plan View dataset was used to capture UGS (refer to Table 2 for detailed definitions of these categories).

Table 4. Example of defining UGS and the datasets by constructs.

Citations		**Wolch et al., 2011 [32]**	**Maas et al., 2006 [18]**
Scales		**Neighborhood**	**City**
Measures	Type of effects	Direct effects (park visiting for activities)	Indirect effects (contribution of natural environments)
	Types of interactions	Intentional interactions	Incidental interactions (no specific activities)
Methods	Measuring approaches	Quantitative (park area within 500 m)	Quantitative (green spaces; 3 km radius)
	Data type	Objective (built environments)	Objective
	Dominant exposures	Accessibility	Availability
Includes water bodies		Yes (several parks with ponds)	N/A
View Types		Plan View	Plan View

Although this classification framework is derived from numerous studies that have conducted UGS measurements, it may not encompass all measurement types (as hinted in the second paragraph of this section). Nevertheless, establishing such a structured system is essential as it facilitates meta-analyses of similar experimental studies conducted both presently and in the future [51]. Furthermore, this framework can serve planners and policymakers, aiding in the formulation of policies to introduce or preserve UGS. In practice, several studies evaluating urban policies using UGS datasets primarily rely on per capita UGS extent [185,186], while more recent research has assessed available parks and accessible water features to examine spatial inequality [187]. A key challenge identified in these studies is the absence of consistent monitoring using standardized UGS datasets. Since the framework is designed to classify dataset characteristics, it can clarify assumptions by explicitly defining UGS for these policies, as well as research.

4.2. Exposure Methods and View Type

This review identifies key characteristics of constructs classified under "Methods" that are closely related to UGS datasets: quantitative, objective, and the three types of exposure—availability, accessibility, and visibility. Although qualitative approaches or subjective methods can also utilize UGS datasets and represent specific exposure assessments, they were not directly considered within the scope of this literature review for two reasons. First, subjective methodologies for collecting individual-level data are highly diverse. For example, the criteria for measuring objectives range from post-experience feelings [105] to regular social interactions of UGS [184]. These methods often illustrate the datasets with GIS-based mapping but do not primarily focus on the GIS-based analysis or techniques. Second, such approaches are predominantly explored in fields outside this review's scope, such as anthropology, sociology, and psychology. Although we included qualitative approaches as a construct of UGS measurements, their application remains limited within the context of this review. Therefore, this discussion focuses on the relationship between UGS datasets and constructs linked to quantitative approaches, objective methods, and exposure assessments, which are further categorized by view type.

While many studies have explored specific aspects of these components, such as comparisons of measurement techniques in Quantitative Approaches, determining buffer

radii for Objective Methods [95], or examining the roles and impacts of Exposure assessments [51], few studies have integrated these constructs into a cohesive framework connecting them to UGS datasets.

Throughout our review of the literature, we found that UGS measurements and datasets categorized by View Type are significantly associated with Exposure assessments, which precede the generation of outcome datasets (Figure 2). This is because exposure assessments are an empirical step in understanding how individuals interact with green spaces. They capture both the extent of green spaces that are perceived or experienced and the datasets used to analyze those perceptions. Specifically, exposure assessments examine factors such as green space availability, accessibility, and visibility, all of which contribute to understanding the physical and visual interactions between individuals and UGS. By analyzing how datasets represent these dimensions of perception, we can establish connections between positional considerations of view types and green space exposure assessments. The following sections provide examples illustrating how different techniques or calculated datasets are positioned within UGS datasets (Figure 3).

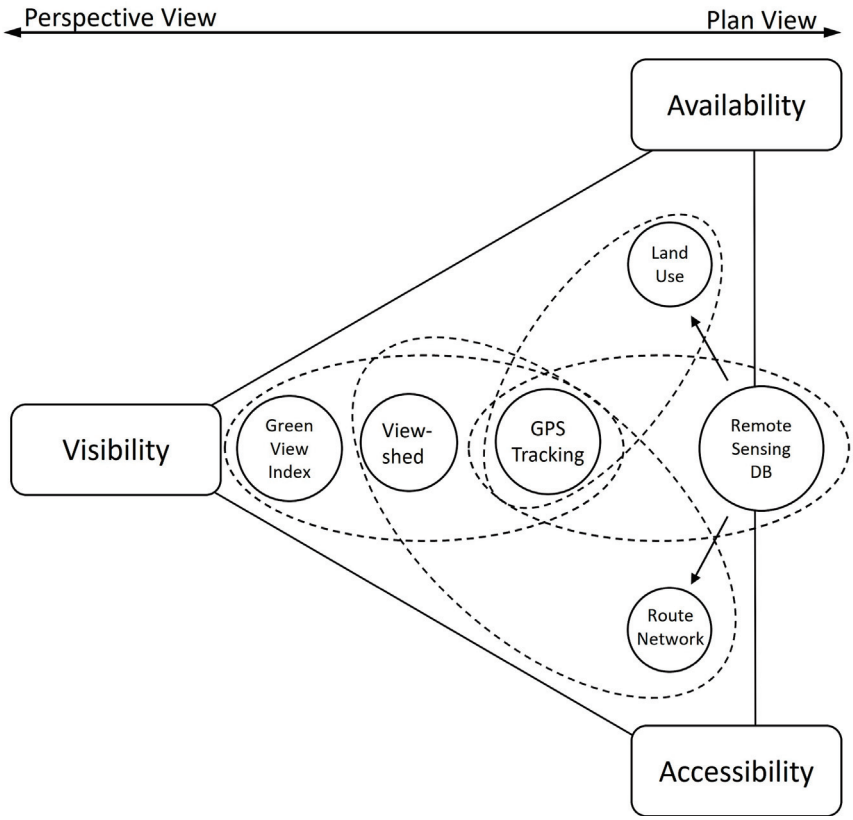


Figure 3. Integration of UGS measurement constructs across View Types and exposure categories (dashed lines represent hybrid techniques integrating UGS datasets).

4.2.1. Datasets by Multi-Spectral Remote Sensing

NDVI, a representative dataset of Remote Sensing DBs, plays a central role in exposure assessments. As a product of multi-spectral remote sensing categorized under Plan View, NDVI datasets provide a comprehensive representation of green spaces that are Available, Accessible, and Visible. Due to this broad applicability, NDVI is widely used. However, without additional analysis, such as user investigation or viewshed analysis, NDVI alone might not explain how green spaces interact with individuals, yet researchers could assume that the space could provide some benefits [8]. Consequently, the use of NDVI as a standalone metric in empirical research has been declining. Instead, Land Use datasets

have emerged as a more suitable alternative and are increasingly utilized due to the connotative usage of space.

To refine analyses for specific participants, GPS devices can be integrated to identify which spaces are available and accessible [87]. GPS devices are particularly valuable as they provide insights into interactions with UGS, assuming the participants' occurring activities and inquiring appreciation of experiences [99]. Furthermore, frequently visited locations in urban areas (e.g., schools, malls, or high-density residential zones) could offer valuable data to explore the long-term benefits of UGS. For instance, the impact of UGS can be investigated by repetitively visiting areas. Therefore, combining UGS facility maps with user-specific information is a recommended approach to examine UGS's lasting effects.

4.2.2. Datasets by Viewshed

Green space datasets derived from viewshed-based techniques and the Green View Index are closely aligned with Visibility in exposure assessments, as they rely on individuals' visual perception of green spaces. These datasets are categorized under Perspective View and are primarily used to measure visibility at the numerous observation points, enabled by advanced calculation capabilities [38,106,136]. Depending on the designated location within a city, viewshed-based datasets could also capture green spaces that are not only Visible but also Available or Accessible. For instance, if a visually adjacent green space is a park or garden, it likely provides both availability and accessibility for users. Such research topics explore the impact of varying visibility levels in urban areas where UGS availability and accessibility remain equal [36].

Additionally, integrating GPS devices can add contextual depth by identifying whether participants are positioned in locations that meet availability and accessibility criteria [41]. For example, by tracking personal and daily travels with GPS, investigating the different visibility of the individuals who live in a place having similar availability and accessibility of UGS. This research design could be applied to many residents living in high-density or urban apartment complexes. This integration allows for more sophisticated assessments of visually perceived green spaces and enhances the understanding of how visibility interacts with other dimensions of UGS exposure.

Particularly, viewshed-based UGS measurements can extend beyond Visibility to address Availability and Accessibility. This is because the analysis fundamentally relies on map data representing vegetation to measure visible green spaces. In urban environments, viewing green spaces plays a critical role in fostering awareness of seasonal changes and appreciating the aesthetic qualities of urban landscapes. Consequently, studies can be designed to account for the dynamic sequence of changes in nature while incorporating aesthetic evaluations. Thus, integrating visibility analysis could become essential when collecting datasets related to UGS Availability and Accessibility.

4.2.3. Consideration of Location and Position

Incorporating the observer's location and position into the relationship between exposure methods and View Type supports more integrative research approaches. These approaches, often referred to as hybrid techniques (as discussed in the previous two sections), can be further refined by focusing on the details of observing locations. A few studies reviewed here demonstrate such techniques by considering both the observer's location and positional aspects, along with individual movements [39]. For instance, individuals may perceive varying amounts of green space depending on whether they are walking, cycling, or driving [41,138,188]. Accounting for these conditions could help identify differing perceptions within the same urban environment.

Although this approach is challenging to implement on a population level, especially in epidemiological investigations, it could be feasible through controlled experiments with smaller sample groups, such as individuals with similar daily routines or occupational patterns [41,97,130]. Expanding this idea further, urban areas also differ in terms of zoning, geography, and land use policies. For example, researchers could identify optimized observation points tailored to the geographic characteristics of urban spaces [138]. In such cases, the context of location becomes a primary factor for applying diverse techniques effectively.

Most studies utilizing UGS measurements and datasets calculate green space exposure based on designated locations (e.g., the centroid points of census tracts or intersections within a road network). However, if observation points are chosen with specific purposes in mind, research can move beyond randomized exposure calculations and uncover the significance of these locations. For instance, green space exposure can be quantified along specific routes (e.g., commutes, recreational paths) [189] or exposure near participants' residences can be analyzed by identifying frequently used pathways [41]. These integrative approaches often involve multiple constructs working together to provide a more comprehensive understanding of UGS exposure.

Moreover, studies employing hybrid techniques to quantify UGS or analyze its datasets are on the rise. However, it is critical to disclose the precise attributes and limitations of the datasets used. This transparency is essential for facilitating longitudinal studies and accurately tracking changes over time. This is particularly important because research findings comparing the quantity of UGS are often utilized to identify opportunities for improving urban environments in specific locations. Practitioners rely on such results and datasets to effectively implement urban planning strategies and zoning regulations [30,37,130]. Therefore, as hybrid techniques grow increasingly complex, providing clear context regarding study areas and dataset attributes becomes essential to ensure the reliability and applicability of research findings.

4.3. Developing a Framework: Plan View and Perspective View in UGS Measurements

In reviewing UGS measurements, numerous academic studies have adopted diverse methodologies, focusing on precisely capturing the extent or characteristics of UGS through novel techniques [13,77,93,188]. For instance, recent studies measuring UGS typically utilize imagery datasets with varying resolutions, such as a 30-m resolution [77] compared to a 1-m resolution [13]. Additionally, the studies consistently utilize multiple measurements for collecting the datasets, ranging from availability to visibility of UGS [93,188]. While the application of novel techniques is essential for enhancing measurement prevision, the fragmented nature of these methodologies can create confusion for planners and other data users in practical applications [8,38].

This confusion arises because each technique often targets specific aspects of UGS, requiring users to select appropriate datasets or measurements based on their specific goals. For example, if an urban designer wants to enhance the visual exposure of UGS in a district and evaluate the subsequent effects of increased visibility, they can refer to datasets or measurement techniques categorized under the Perspective View. This highlights the importance of organizing UGS measurements into structured frameworks, such as Plan View and Perspective View, to help users effectively navigate and apply appropriate techniques.

To promote the practical use of UGS measurements, it is crucial to determine which measurements best reflect the needs of the community and the characteristics of UGS that need to be implemented. As for the end-users, we concentrate on the simplification of diverse measurement approaches to identify the characteristics. Consequently, we provide a classification framework for UGS measurements based on View Types of the

representing greenery, intended for use by urban designers, planners, and stakeholders (see Table 3 for detailed measurements and Figure 4 for the overview of the classification). The classification of UGS measurements accommodates a variety of geospatial datasets, each suited to different research purposes (Figure 4). In the urban context, both Plan View and Perspective View classifications are compatible with existing and newly developed UGS datasets, as they attempt to encompass measurable aspects of UGS that can be perceived and assessed through remote sensing.

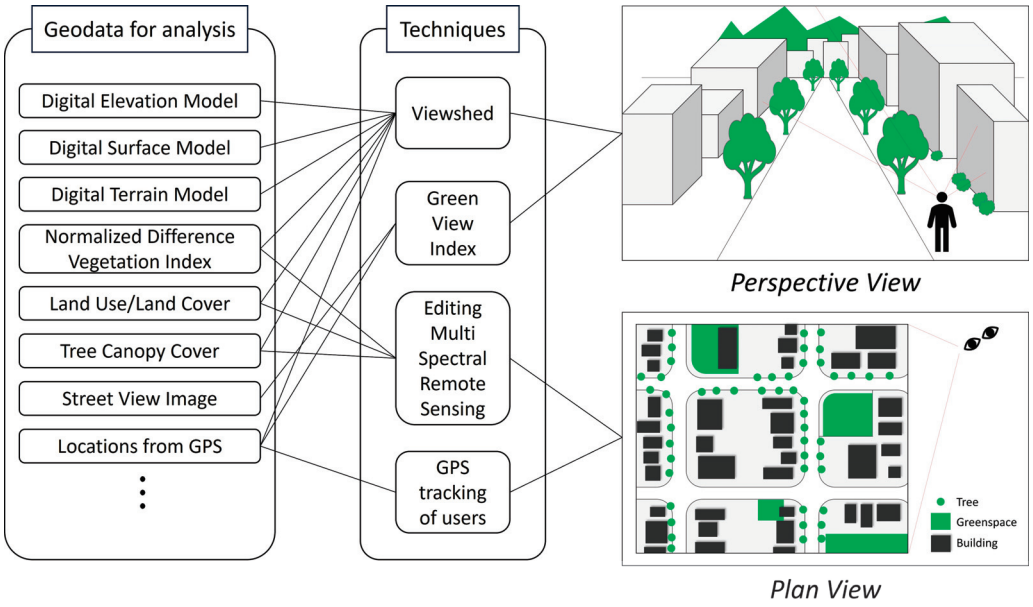


Figure 4. Classification of UGS datasets by GIS-based analysis and techniques.

For example, consider a scenario where a vast patch of natural areas (e.g., urban forests without trails or public accessibility) might not promote physical activity due to limited accessibility, making it unavailable to the public. In such cases, focusing on the perspective view—which aligns measurements with pedestrian pathways and ground-level interactions—would be more appropriate [25,74]. Conversely, data collected through the GPS tracking of users, which reflects individuals' engagement with greenness through the extensive movement patterns, can be classified under plan view as it pertains to the broader spatial distribution and accessibility of UGS [99]. However, if these data are joined with some type of viewshed analysis, then it could serve to also function as a perspective view [106,136]. Therefore, it is essential to treat the plan view and perspective view as distinct classifications within a single study to capture the multifaceted constructs of UGS in Table 2. This dual classification ensures that measurements are tailored to the specific perspectives from which users interact with green space. This classification framework offers several benefits:

1. Consistency in data management: By categorizing measurements into Plan View and Perspective View, the framework promotes consistency in data collection and management across different studies. This consistency facilitates meta-analyses and comparative research, enhancing the robustness of findings related to UGS and health outcomes [51].
2. Practical application for policymakers and planners: The framework serves as a practical roadmap for city planners and policymakers, aiding in the formulation of policies related to the introduction or preservation of UGSs. Measurement data organized within this framework can be utilized to demonstrate how specific types of UGS initiatives impact residents, thereby supporting informed policy decisions [15,190].

3. Enhanced understanding of UGS impacts: By distinguishing between aerial and ground-level perspectives, the framework allows for a more nuanced understanding of how UGS influences various aspects of urban life, such as physical activity, mental well-being, and environmental quality [112,136].
4. Support for health-related studies: The framework underscores the necessity for health-related studies examining UGS to define which health-related factors correspond to specific constructs. Within this framework, appropriate measurements and datasets can be selected to foster mutual understanding between researchers and end-users, supporting long-term, consistent series of studies that provide improved causal inferences between UGS and health outcomes [23,56].

4.4. Future Direction of UGS Measurements

The future direction of UGS measurements is expected to involve the development of new devices and the integration of novel methods through interdisciplinary approaches. While existing measurements have primarily focused on quantifying the accurate amount of vegetation, future advancements will aim to incorporate quality evaluations and subjective assessments. A variety of emerging devices and methods will likely be applied to better capture the value of UGS and the extent of human interactions with these spaces [8,54,182].

Novel technologies, such as virtual reality, are being utilized to evaluate the experiential aspects of UGS, replacing traditional visual experiences to assess the indirect impacts of greenery [46,47]. Several studies have attempted to identify individual perceptions within virtual environments, focusing on the attention-restorative effects of UGS [48,49]. Additionally, the urban digital twin approach, which replicates urban environments in virtual spaces, could offer a method for exploring the influence of UGS by collecting data on both existing and perceivable green spaces [191]. These advancements in data collection and analysis could further refine the construct-based classification. For instance, scale considerations could be expanded to account for virtual representations of UGS.

Advancements in algorithms, particularly Convolutional Neural Networks (which are commonly classified under artificial intelligence), have been developed to improve the accuracy of visually perceived UGS by identifying street trees through perspective view imagery [44]. In line with that advancement, those deep learning algorithms can evaluate and predict aesthetic factors through street view images by using training sets of participants involved [42].

Advanced recording devices are also providing new data sources. Smaller camera devices mounted on individuals are now capturing street view images in areas previously inaccessible to car-mounted cameras [192], but they can also capture imagery of user interactions (e.g., hiking, walking, cycling) where these data were not available previously. Likewise, Uncrewed Aerial Vehicles can be used to capture hyperspectral images, such as near-infrared imagery, to calculate vegetation indices. The regularity of these data collection techniques could expand the construct to consider how time and seasonality influence the definition.

UGS measurement methods are becoming increasingly diverse, allowing for improved accuracy alongside technological advancements [8,38,42]. As data collection methods continue to diversify, the importance of organizing and categorizing these data will also grow. The proposed classification in this study offers a structured approach that enhances the practical and interdisciplinary application of UGS measurements. By using this classification, measured datasets can become more meaningful and adaptable across various fields, supporting a more comprehensive understanding of UGSs.

5. Conclusions

This review offers a thorough examination of a diverse range of methodologies and datasets used to measure UGS. These have been formalized into a framework for their classification and application. The framework is grounded on a construct-based definition of Urban Green Space into five different elements: scale, measures, methods, green/blue spaces, and view type. In addition to the construct approach, the review provides an overview of the evolution of UGS measurements from basic approaches in quantifying green spaces to more integrative and experiential techniques meant to quantify visibility, accessibility, and availability. These techniques underscore the critical role of exposure assessments in bridging both the physical and perceptual aspects of UGS.

This review also emphasizes the potential of hybrid techniques that combine quantitative and qualitative approaches, such as integrating GPS data with visibility analyses or applying multi-scale methods to capture user-specific interactions with UGS. These integrative methods address gaps in understanding how green spaces impact diverse populations and urban environments.

While UGS research continues to advance and play a role in policy, variability in dataset attributes, differences in geographic contexts, and the lack of consistent definitions across studies can limit generalizability and comparability. To address these limitations, transparency in dataset characteristics and methodological choices is essential. Practitioners and policymakers require reliable, clearly communicated data to inform urban planning strategies and enhance UGS accessibility and usability.

Finally, this review points to future directions, including the refinement of UGS measurement frameworks, the development of longitudinal data to assess green space changes, and the application of novel tools such as artificial intelligence-driven semantic segmentation technologies. By advancing these methodologies and addressing current challenges, UGS research can continue to provide meaningful insights for urban development and improve the quality of life for urban residents.

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Which Factors Enhance the Perceived Restorativeness of Streetscapes: Sound, Vision, or Their Combined Effects? Insights from Four Street Types in Nanjing, China

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Abstract: Streetscapes play a critical role in restorative landscapes, offering opportunities for promoting public well-being. Previous studies have predominantly examined the influence of visual and auditory stimuli on perceived restorativeness independently. There is a limited understanding of their interactive effects. In this research, 360 participants completed a series of experiments considering four distinct street types, including visual comfort assessment, acoustic environment assessment, and perceived restorativeness. They were assigned to a control group and one of three experimental groups, each receiving specific enhancement: visual stimuli, auditory stimuli, or a combination of audiovisual stimuli. The findings revealed that the experimental groups reported a greater sense of restorativeness compared to the control group. Notably, auditory stimuli demonstrated a more pronounced restorative effect than visual stimuli, while limited differences were found between auditory and audiovisual stimuli. The differences in experimental outcomes among the four street types are compared and discussed, highlighting context-specific guidelines for enhancing streetscape restorativeness. The research findings highlight enhancing the masking effect of soundscape in street environmental design. The study adds a novel multi-sensory approach to the current body of research on restorative landscapes, providing significant insights for the planning and design of streetscapes.

Keywords: streetscape; sound; vision; restorativeness; audiovisual interactions

1. Introduction

Streets occupy approximately 25–35% of all developed urban land [1], representing a significantly larger portion of urban space compared to parks and other public areas. Given their integral role in the cityscape and their proximity to homes, streets serve as a primary location where residents spend a considerable amount of their outdoor time [2]. Streetscapes, encompassing both the physical and experiential components of streets, are an essential part of urban green infrastructure. They incorporate natural elements, including trees, shrubs, and water features, alongside human-made elements such as pavements and street furniture, to establish environments that are both visually appealing and functionally integrated. Within the broader concept of restorative landscapes—environments designed to promote psychological and physiological recovery—streetscapes have the potential to significantly enhance human well-being and alleviate stress [3]. A thoughtfully designed streetscape goes beyond merely addressing health and safety concerns; it also fosters the

cultural identity of a community and stimulates economic growth and contributes to the visual image of sustainable cities, promoting tourism and overall urban success [4]. Despite their close connection to daily life and their potential impact on psychological well-being, streetscapes have not received significant attention in academic research concerning their restorative potential. This oversight has led to a lack of thorough guidelines for the effective design of streetscapes [5].

Existing research focusing on streetscape restorativeness has primarily focused on visual aspects [4,6], such as the green view index [7], green coverage [8,9] and street segmentation elements [10,11]. These visual elements are central to landscape planning and design, as they shape the aesthetic and functional qualities of urban spaces. Aside from visual effects, audition is a critical component of the five human senses. Soundscapes are increasingly recognized as a key factor in creating restorative environments [12]. The soundscape, which encompasses both natural sounds like bird calls and rustling leaves, as well as anthropogenic sounds such as traffic and conversations, provides a unique auditory experience that captures the essence of a place [13]. This auditory dimension, though sometimes subtle, can have a profound impact on our emotional reactions, eliciting a wide range of feelings from tranquility to discord [14]. However, few studies have combined auditory and visual perceptions to understand how people experience streetscapes [15].

Streets are categorized in various ways based on factors such as location, material, traffic, and function. For example, the US National Capital Planning Commission [16] distinguishes between radiating and edging streets, connecting and traversing streets, as well as local streets based on their geographical context. In terms of roadway functionality, the Federal Highway Administration (FHWA) [17] of the U.S. Department of Transportation (DOT) classifies roads into four main categories: interstates, other arterials, collectors, and local roads. Additionally, the *Nanjing Street Design Guidelines* categorize streets according to their relationship with surrounding land and buildings, identifying living streets, traffic streets, comprehensive streets, and service streets [18]. Previous research has largely focused on commercial streets [19] and living streets [20] in isolation. Only a limited number of studies on restorative environments have sought to evaluate the restorative potential of various street types [21].

Given the aforementioned research gaps, this study seeks to investigate the interaction effects of vision and sound on the perceived restorativeness of the streetscape, considering varied street types. Specifically, the aim is to examine the following two research questions:

Research Question I: Can vision and sound independently enhance restoration when considering different street types?

Research Question II: Can the combination of vision and sound enhance restorative effects compared to their independent roles, when considering different street types?

2. Literature Review

2.1. Restorative Landscape

"Restoration" refers to the process of regaining physical, psychological, and social abilities lost due to external environmental pressures [22]. This concept has been widely studied in the context of urban environments, where researchers have explored restorative potential from various perspectives, including housing, transportation, and—most notably—natural environments and urban green spaces. Restorative landscapes aim to foster psychological and physiological recovery by integrating multiple environmental dimensions [23,24]. These include natural, built, symbolic and social environments [24]. Theoretical developments in this domain have led to several frameworks that explain the factors influencing perceived restorativeness. Two prominent theories are the Attention Restoration Theory (ART), proposed by Kaplan et al. [25], and the Stress Reduction

Theory (SRT), posited by Ulrich et al. [26]. The former is a psycho-functionalist theory, emphasizing mental fatigue, while the latter is a psycho-evolutionary theory, focusing on physiological stress. Both theories share a common foundation: the idea that natural elements, such as greenery, water features, and open spaces, can significantly enhance human well-being by providing opportunities for mental and physical recovery [26,27].

The ART, in particular, delineates four crucial components of restorative environments: being away, fascination, extent, and compatibility [25]. These components are defined as follows: "Being away" refers to the psychological detachment from daily stressors and responsibilities, providing a mental break. "Fascination" indicates the ability of an environment to hold attention effortlessly. "Extent" relates to the quality of restorative environments that encourages one to feel totally immersed and engaged. "Compatibility" ensures that the environment aligns with the individual's goals and preferences, fostering a sense of belonging and ease.

Building on ART, Hartig [22] expanded the four dimensions of restorative environments by creating the Perceived Restorativeness Scale (PRS), which evaluates the restorative attributes of different settings and has been widely applied in natural, urban, and indoor contexts. Research endeavors grounded in the ART framework have predominantly centered on visual stimuli [28], often neglecting auditory components or failing to rigorously control for acoustic parameters. To address this gap, Payne [29] developed and validated the Perceived Restorativeness Soundscape Scale (PRSS). This scale, grounded in the four dimensions of ART, evaluates individuals' perceptions of a soundscape's capacity for psychological restoration. Collectively, these measurements provide a more comprehensive understanding of how both visual and auditory components influence the restorative qualities of urban environments.

2.2. Effects of Vision and Audition on Restorative Streetscape

Streetscapes, as a critical component of urban restorative environments, significantly influence human psychological restoration through differentiated activity patterns. Drawing upon Gehl's classification system [30], streetscape activities can be categorized into three dimensions: necessary, optional, and social activities. Necessary activities encompass obligatory routines such as commuting, work-related travel, and essential shopping, where environmental quality plays a relatively minor role in user engagement. Optional activities include utilitarian walking (e.g., combining shopping with café visits) and leisure-oriented strolling (e.g., walking children or pets). The third category, social activities, specifically involves interpersonal interactions and communal recreation. The latter two categories exhibit heightened sensitivity to environmental design attributes, serving as crucial mediators for sustaining public engagement and amplifying restorative effects through enhanced environmental design.

Emerging studies have shown that well-designed street environments can replenish psychological resources, reduce stress levels, and elicit beneficial physiological responses [31,32]. Within the environmental perception research paradigm that emphasizes the "environmental stimuli–perceptual feedback" framework, other related influencing factors are considered as contextual setting, with a greater focus on how individuals perceive, interpret, and respond to environmental stimuli through sensory mechanisms. To enhance these restorative benefits, scholarly discourse has predominantly focused on visual street design indicators, such as spatial morphology [33,34], functional aspect [35], specific street design elements [5,11], ecological sustainability [36], and identity-related factors [37,38].

For example, Lindal et al. [10] evaluated the presence of trees, flowers, and flower beds on humans' judgements of restoration likelihood. Jiang et al. [8], in an experiment involving video recordings of street foliage, showed a positive linear relationship between

perceived stress and green coverage. More recently, Wu et al. [11] evaluated the impacts of different street elements (i.e., wall, tree, etc.) on restorative perception, combining street view images, deep learning, and space syntax. Additionally, Navarrete-Hernandez et al. [39] assessed the impact of levels and types of street greenery on people's perceptions of happiness using an image-based randomized controlled trial.

Beyond vision, the auditory environment also contributes significantly to restorative streetscapes. Research has identified two aspects of restoration related to perceived acoustic environments: (1) the direct positive influence of high-quality acoustic environments (e.g., natural sounds), and (2) the mitigating effect of access to such environments for individuals chronically exposed to noise pollution [40]. Epidemiological evidence regarding the intrinsic benefits of acoustically high-quality areas—such as green spaces, wilderness, or water—remains limited. Regarding the mediating role, quiet environments near residential areas can reduce noise annoyance and improve physiological outcomes like sleep quality and blood pressure. Furthermore, a temporary break from environmental noise may also counteract its adverse health effects [41]. The restorative potential of soundscapes is fundamentally shaped by the complex interplay of physical environmental characteristics. A notable investigation by Hong et al. [42] employed soundwalk methodology to investigate how urban functions influence the soundscape in streets, taking into account the relationships among human behaviors, the sound environment, and various acoustic indicators.

Controlled experiments further corroborate these findings. Exposure to natural sounds—whether in parks, urban areas, or virtual environments—consistently enhances mood, well-being, and perceived quality of life. For instance, Zhang [43] used a psychological scale to measure the restorative benefits of soundscapes by watching soundscape videos in a laboratory, while other studies examined the influence of sound on the perceptions of enclosures and restoration in urban street canyons with varying height-to-width ratios [44]. Collectively, this research underscores that urban soundscape, particularly in dense cities, profoundly influence individuals' restorative experiences.

A limited but growing body of research has examined the compounding effects of vision and sound on streetscapes [38]. For example, using images of streetscapes with a combination of vegetation and water features, Hong and Jeon [45] provided principles for designing sound and visual components for the enhancement of urban soundscapes. Zhao et al. [46] utilized a machine learning approach to sense urban soundscapes from street view imagery and uncover the relationship between visual features and human soundscape perception. Ren et al. [47] also explored the perceived characteristics of the audiovisual environment in urban pedestrian streets with traffic noise and their influences on the environmental health of these streets. These studies collectively contribute to a deeper understanding of how streetscapes can promote psychological restoration through multifaceted design.

2.3. Limitations in Audiovisual Perception Research Concerning Streetscape

Despite advancements, current investigations into the audiovisual perception of streetscapes still exhibit certain limitations. Firstly, the majority of research relies on cross-sectional data, which do not adequately capture the long-term dynamics of environmental changes [48]. For instance, seasonal variations—such as changes in vegetation density—can significantly alter the visual and auditory characteristics of streetscapes. These temporal changes are often overlooked in cross-sectional studies, which fail to account for how such dynamic factors influence public perception over time. Secondly, many studies focusing on environmental perception tend to analyze visual or auditory elements in isolation, thereby lacking a comprehensive examination of both aspects [49]. Thirdly, existing audiovisual

research has explored associations among various environments and perceived restoration, such as urban and natural parks, urban squares, and commercial streets [50]. Nonetheless, there is an absence of studies that provide a thorough evaluation of multiple street types and their interconnections.

The public's audiovisual perceptions of different types of urban streetscapes are an integral part of reaching Sustainable Development Goal (SDG) 11—Building sustainable cities and communities. Streets exhibit a wide spectrum of types, distinguished by varying architectural designs, degrees of green space integration, and patterns of pedestrian activity. With this in mind, the present study is an attempt to conduct an assessment of the public's audiovisual perceptions, taking into account seasonal variations across diverse streetscapes, by employing time-series imagery data of streetscapes.

3. Materials and Methods

3.1. Study Area

The study area was Nanjing, Jiangsu Province, one of the first batches of urban design pilot cities approved by the Ministry of Housing and Urban-Rural Development of China (Figure 1). According to the *Nanjing Street Design Guidelines* [18], streets are classified into four types based on the functional relationship of land and buildings along the route. These include traffic, living, comprehensive, and service streets. As shown in Figure 2 and Table 1, the streets selected as case studies are specifically highlighted in the guidelines, confirming that they represent the different street types found in Nanjing.

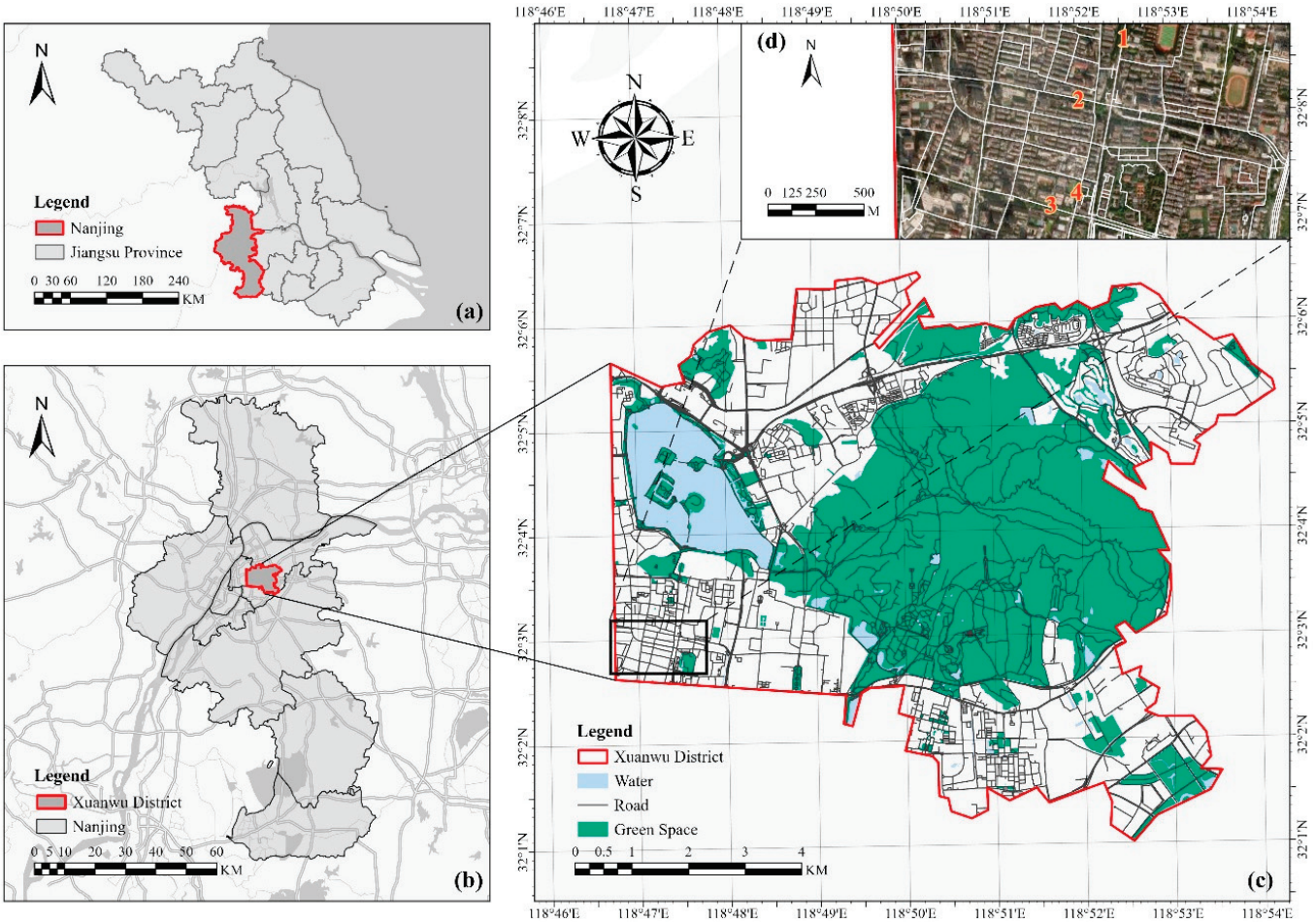


Figure 1. Location of the streets selected as case studies. (**a**) Jiangsu Province, (**b**) Nanjing City, (**c**) Xuanwu District, (**d**) Distribution of selected streets: (1) Taiping North Road, (2) Zhujiang Road, (3) Changjiang Road, (4) Beiting Lane.

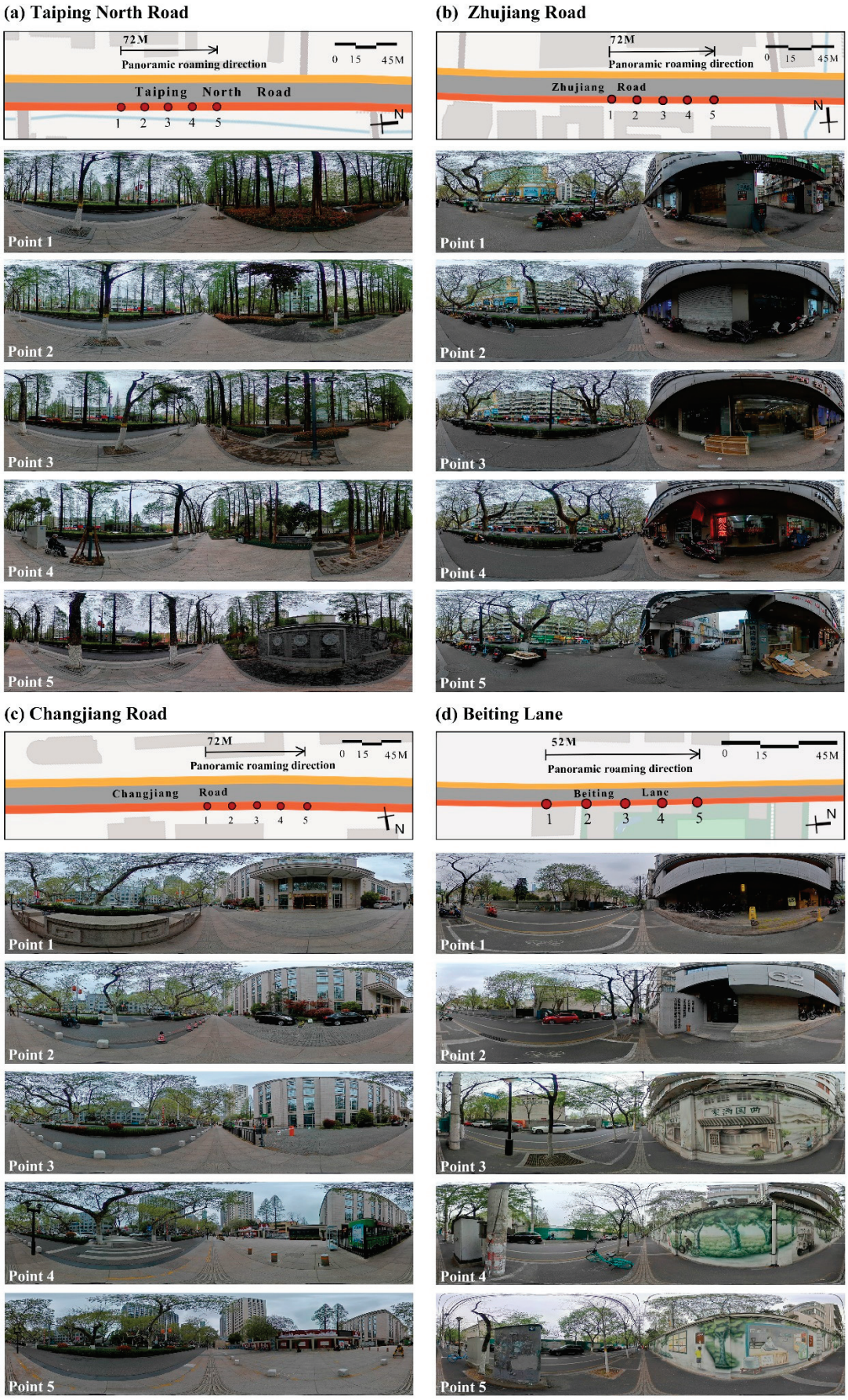


Figure 2. Images of the streets selected as case studies. (**a**) Taiping North Road, (**b**) Zhujiang Road, (**c**) Changjiang Road, (**d**) Beiting Lane.

Table 1. Street types as classified in the Nanjing Street Design Guidelines.

Street Functional Type	Description	Typical Street
Traffic street	Streets with a predominantly non-open interface along the street, with a predominantly pass-through traffic and a strong transit-oriented function.	Taiping North Road
Living street	Streets along which commercial facilities, cultural facilities and public service facilities predominate, and where the public life and activities of citizens are more concentrated.	Zhujiang Road
Comprehensive street	Streets with a mix of functional attributes and interface types of parcels and buildings along the street, with a mix of traffic and amenities.	Changjiang Road
Service street	Streets along which there is a predominantly non-open interface and which are primarily used to address logistical motorized traffic and collectors.	Beiting Lane

3.2. Stimulus

3.2.1. Visual Stimuli

Panoramic street image data were collected on the selected sample streets using the RICHO THETA SC2 device (RICHO Company, Ltd., Tokyo, Japan). To maintain the continuity and authenticity of the walking experience, five sampling points were established along the selected streets, spaced at intervals ranging from 13 to 18 m, depending on the streets' length (Figure 2). According to the China Health Association [51], the average height for adult females in China is 1.58 m and for adult males, 1.697 m. Therefore, a height of 1.5 m, simulating eye-level height, was maintained by utilizing a tripod during the image capture process. To mitigate the potential impact of weather conditions on the experimental outcomes, the image capture was conducted at 11:00 a.m. on cloudy days. To effectively illustrate the time variation on the streets, we captured photographs two months apart during spring, specifically on 5 March 2024, and 2 May 2024, from identical locations along each street.

To reduce the impact of lighting variations and the presence of pedestrians during the collection periods, Photoshop CC 2019 was employed to standardize the lighting conditions of the sample images for each street at each designated point. This adjustment ensured that the panoramic images maintained a clear forward field of view, free from close pedestrian disruptions. Given the limited social spaces on streets, we focused on visual exposure scenarios corresponding to necessary/optional walking activities based on Gehl's activity classification theory [30].

This study focuses on the green view index (GVI) as the core visual metric, given its established role as one of the strongest visual predictors of walking satisfaction [52]. While streetscape quality involves multidimensional factors such as safety (e.g., traffic control) and livability (e.g., seating facilities), previous evidence shows that natural elements like trees and grass demonstrate the strongest correlation with visual preference compared to cultural facilities or water bodies [11,53]. This supports our research approach of revealing vegetation dynamics through dual-temporal GVI comparisons.

Following this, PSPNet was employed to assess variations in the GVI of the streetscape. By leveraging the ADE20K dataset, we classified pixel points within the panoramic images, identifying various landscape components such as the sky, buildings, sidewalks, trees, and grass, assigning category a distinct color (Figure 3). This allows for the calculation of proportional changes in different elements within images captured at the same street location on two separate occasions, thereby serving as a reference for alterations in the GVI (Table 2).

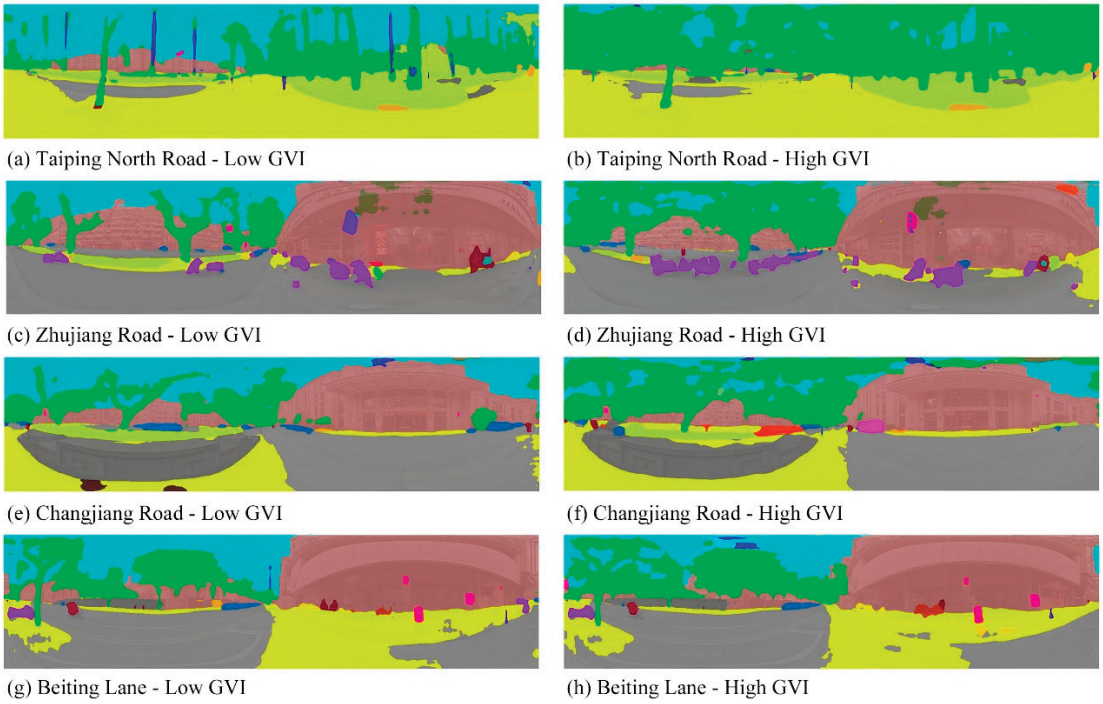


Figure 3. Examples of streetscape image semantic segmentation (one sample point per street). Color code: sky (blue), tree (green), grass (bright green), road (grey), pavement (yellow), building (brown), wall (dark grey), motorcycle (purple).

Table 2. Street GVI statistics.

Street Name	Time	GVI/% Point 1	Point 2	Point 3	Point 4	Point 5	Average/%	Variation/%
Taiping North Road	First Capture	28.96	29.41	27.17	25.81	18.70	26.01	+19.28
	Second Capture	55.54	47.61	41.54	44.66	37.09	45.29	
Zhujiang Road	First Capture	7.35	11.58	7.56	9.68	7.42	8.72	+9.85
	Second Capture	19.26	19.47	16.34	18.14	19.64	18.57	
Changjiang Road	First Capture	13.97	18.72	19.88	17.13	22.70	18.48	+8.83
	Second Capture	23.17	28.31	26.75	30.00	28.33	27.31	
Beiting Lane	First Capture	10.51	8.50	7.70	17.48	10.85	11.01	+10.72
	Second Capture	14.54	17.86	15.57	35.89	24.78	21.73	

3.2.2. Auditory Stimuli

A three-minute audio recording of street sounds was captured using a Zoom H3-VR recorder at locations representative of the typical acoustic characteristics of each street (refer to Table 3). Concurrently, during the collection of image and sound data for the experiments, sound levels were assessed and recorded at each specified location along all experimental routes utilizing a smartphone application that features a dB Meter. The primary sound levels recorded at each point (Figure 2), along with the average sound levels for each street, are presented in Table 3.

The street sounds collected were processed using Adobe Audition CC (2021) software to create a three-minute original sound piece for each street. Furthermore, to effectively mimic an improved sound environment, birdsong was mixed and combined with the original sound. The survey was carried out in late spring, leading to the selection of resident birds over migratory species, given the colder winter conditions in Nanjing. The Daurian Redstart (*Phoenicurus auroreus*) was chosen, which is a common species in Nanjing, typically inhabiting shrubs and low trees in residential areas as well as urban fringes and forests.

Table 3. Street sound-level statistics.

Street Name	Sound Level/dB					Average/dB
	Point 1	Point 2	Point 3	Point 4	Point 5	
Taiping North Road	63	64	52	69	57	61
Zhujiang Road	69	58	70	63	71	66.2
Changjiang Road	72	70	70	71	66	69.8
Beiting Lane	59	61	55	59	69	60.6

Each added sound clip was measured and calculated by the Decibel Addition Formula in accordance with GB/T 3222.1-2022: Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 1: Basic Quantities and Assessment Procedures [54]. The process involves taking each individual decibel level, reverting it to its original linear scale, aggregating these values, and subsequently converting the total back into a decibel level. After the birdsong was added to each targeted sample, the total decibels were increased by merely 1~2 dB, which is below the realm of human-perceived changes in sound level. In total, eight three-minute audio segments were produced, each street corresponding to one segment of original street audio and one segment featuring the edited street audio combined with the birdsong.

3.2.3. Panoramic Roaming Scene

The 720yun platform (https://www.720yun.com/, accessed on 5 May 2024) was used to develop VR panoramic roaming scenes, with links to various scenes available in Table S1 in Supplementary Materials. Users can interact with the environment at each location by dragging the screen onto the webpage and can navigate to additional points by clicking the arrow icon, akin to the Google Street View experience. As mentioned in Sections 3.2.1 and 3.2.2, panoramic images from five locations on each street were uploaded to the 720yun platform, categorized by different street types and GVI levels. Meanwhile, the original street audio and a mixed audio track featuring birdsong (hereafter referred to as birdsong audio) were incorporated where applicable. Consequently, four distinct roaming scenes were created for each street type: control group (original sound with low GVI), sound group (birdsong with low GVI), vision group (original sound with high GVI), and combination group (birdsong with high GVI) (Figure 4).

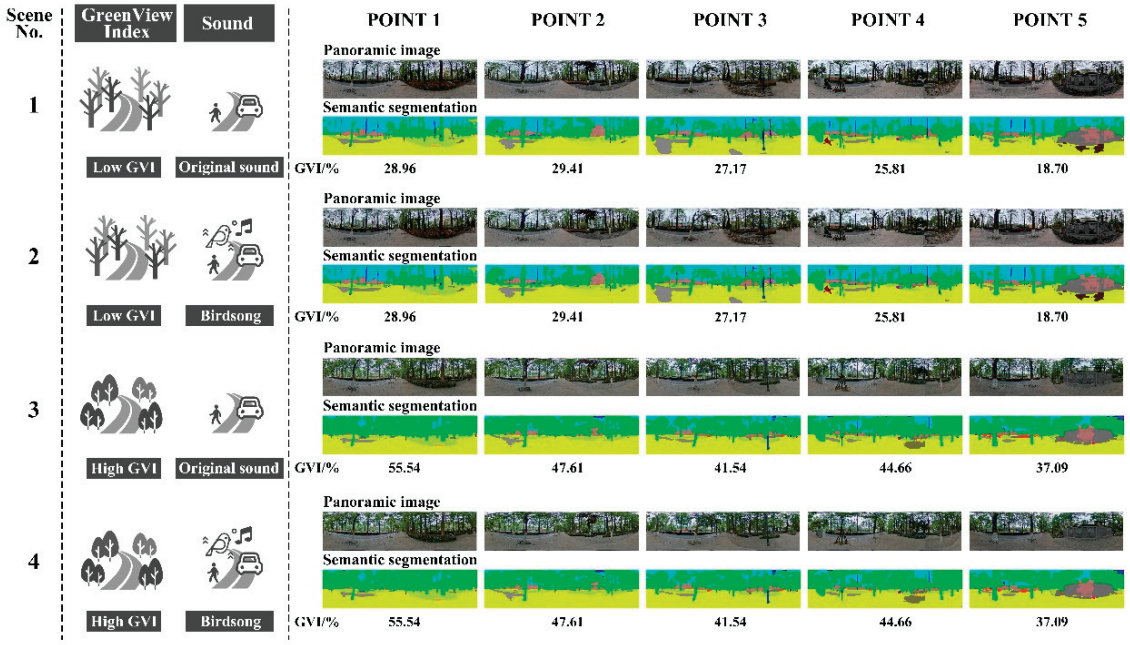


Figure 4. Illustration of experiment design (using Taiping North Street as an example).

3.3. Measurements

3.3.1. Overview

An online survey using a randomized scenario experimental design methodology was conducted through the open platform, Credamo (https://www.credamo.com/, accessed on 10 May 2024). This platform boasts an online sample base exceeding 3 million participants and has demonstrated effectiveness in previous research [55], which can therefore ensure data validity and sample recruitment. The questionnaire consisted of three parts. The first section gathered demographic details about the participants, including gender, age, occupation, education level, residential environment, and psychological health status. The second and third sections involved one control group and one of the three experimental groups (sound group, vision group, or combination group) with related questions. These questions included visual comfort assessment, acoustic environment assessment, and ratings based on the revised PRS.

3.3.2. Psychological Health Status

To understand the pre-test psychological health status of the participants, two entries in the K6 scale (Kessler 6 Psychological Distress Scale, K6) were selected [56]. Participants were asked to rate two psychological conditions, "upset or irritable" and "depressed to the point of not being able to feel happy in any way", based on their psychological condition in the past month, with responses including "don't feel that way", "some of the time", "more of the time", "most of the time", and "all of the time". Each of the five responses received a score ranging from 1 to 5 points, where higher scores for two entries suggested the presence of more severe psychological issues.

3.3.3. Visual Comfort Assessment

In light of the varying characteristics of typical landscape elements across different street types, distinct assessment criteria for visual comfort were employed. Specifically, all participants evaluated the visual comfort of "green space" and "sidewalk" within the four scenes. Furthermore, participants assigned to specific street types evaluated relevant visual elements, including "vignette facilities (seating benches, scenic walls, etc.)" on Taiping North Road, "stores along the street" on Zhujiang Road, "auxiliary facilities (guardrails, road stakes, etc.)" on Changjiang Road, and "vignette facilities (scenic walls, etc.)" on Beiting Lane. Each item was evaluated using a five-point Likert scale ranging from "1 = very uncomfortable" to "5 = very comfortable".

3.3.4. Acoustic Environment Assessment

Pleasantness, quietness, and appropriateness were selected as the indicators for acoustic environment assessment [57,58]. Pleasantness and quietness pertain to the subjective feelings of enjoyment or tranquility experienced by individuals in relation to the acoustic surroundings, while appropriateness reflects the extent to which the acoustic environment aligns with the visual environment. Building on Osgood [59], the acoustic environment was evaluated using a semantic differentiation scale ranging from 1 to 5, comprising "unpleasant-pleasant", "unquiet-quiet", and "unsuitable for the visual environment-compatible with the visual environment", according to their perception of the acoustic environment.

3.3.5. Perceived Restorativeness Scale (PRS)

The Perceived Restorativeness Scale (PRS), based on the Attention Restoration Theory, was developed and validated by Hartig [22] and has been widely utilized in the evaluation of restorative benefits in the physical environment. In the field of soundscape restoration, a Perceived Restorativeness Soundscape Scale (PRSS) was developed and tested to assess

perceptions of a soundscape's potential to provide psychological restoration [29]. Building on PRS and PRSS, we developed a revised version of PRS that considered both visual and auditory environments, containing three statement items in each dimension: fascination, being away, compatibility, and extent (Table 4).

Table 4. The revised Perceived Restorativeness Scale.

Dimensions	PRS Statement
Fascination (F)	F1-I find this visual and sound environment appealing. F2-There is so much to explore and discover here. F3-I would like to spend more time looking at my surroundings.
Being away (B)	B1-The visual and auditory environment here helps me to relax my mind. B2-The visual and auditory environment here makes me feel free from the stress of daily work for a while. B3-The visual and auditory environment here lets me take a break from my daily routine and responsibilities.
Compatibility (C)	C1-The visual and auditory environment fits with my personal preferences. C2-I can do the things I like to do here. C3-I rapidly get used to seeing the visual environment and hearing this type of auditory environment.
Extent (E)	E1-The sounds I am hearing seem to fit together quite naturally with this place I see. E2-It's a place that allows me to fit in without feeling constrained. E3-It's a place that inspires a lot of good thoughts in me.

3.4. Experimental Design

Each participant was randomly assigned to one control group and one of the three experimental groups (Table 5). To eliminate potential order bias, the order in which participants viewed the two scenes was randomized via the Credamo platform. Participants were asked to take part in the experiment only on the computer side and in a tranquil setting to enhance the overall roaming experience. The experimental procedure and time required for each phase are shown in Figure 5.

Table 5. Street sample groupings.

Street Name (Function)	Test Group	Group Name	GVI	Sound Type
Taiping North Road (Traffic street)	1	Control	Low	Original sound
		Sound	Low	Birdsong
	2	Control	Low	Original sound
		Vision	High	Original sound
	3	Control	Low	Original sound
		Combination	High	Birdsong
Zhujiang Road (Living street)	4	Control	Low	Original sound
		Sound	Low	Birdsong
	5	Control	Low	Original sound
		Vision	High	Original sound
	6	Control	Low	Original sound
		Combination	High	Birdsong
Changjiang Road (Comprehensive Street)	7	Control	Low	Original sound
		Sound	Low	Birdsong
	8	Control	Low	Original sound
		Vision	High	Original sound
	9	Control	Low	Original sound
		Combination	High	Birdsong
Beiting Lane (Service street)	10	Control	Low	Original sound
		Sound	Low	Birdsong
	11	Control	Low	Original sound
		Vision	High	Original sound
	12	Control	Low	Original sound
		Combination	High	Birdsong

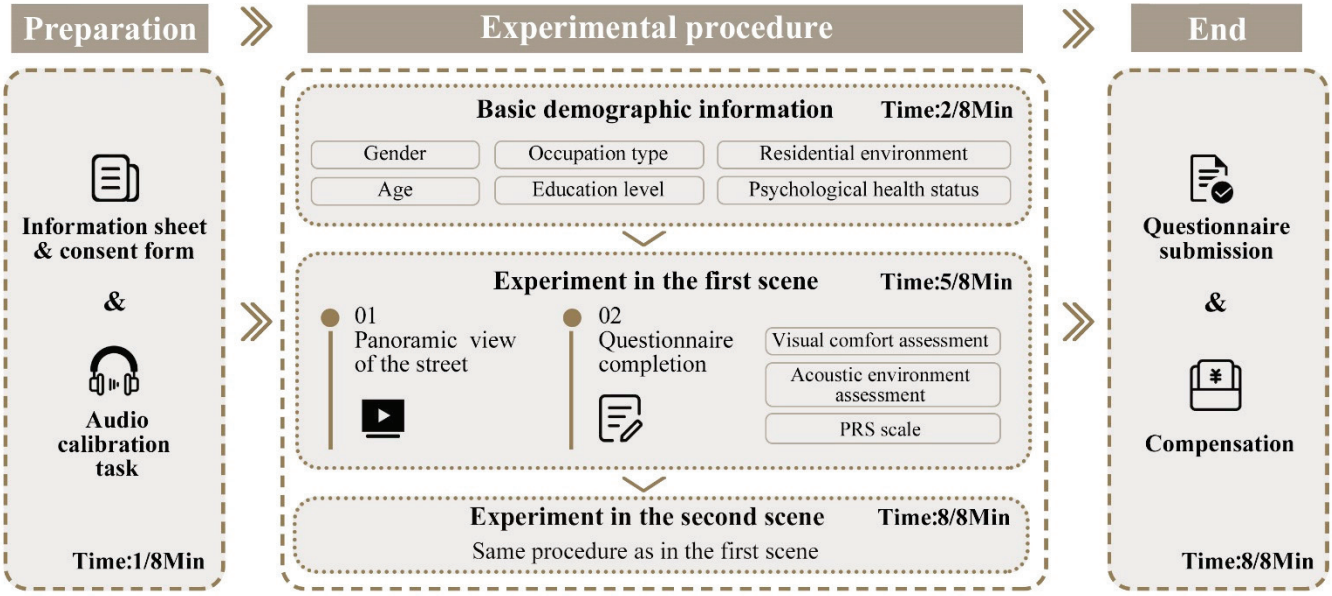


Figure 5. Experimental procedure. Note: The arrows show the direction of progression.

Prior to starting the experiment, the participants were briefly introduced to the research aims and process. They were asked to do an audio calibration task to make sure the experimental samples played the sounds correctly and to improve the consistency of the sound presentation among different people. Then, they were asked to fill in the socio-demographic information and pre-test psychological health status. The participants were then directed to click on a web link to access the first panoramic street walkway, where they were encouraged to visualize themselves within the depicted environment and to immerse themselves in the experience for a minimum of two minutes. Then, they were asked to complete the visual comfort assessment, the acoustic environment assessment, and the PRS. Following the same procedure, participants were asked to view the second scene and complete the questionnaires. Finally, they were allowed to leave the experiment.

3.5. Statistical Analysis

The collected questionnaires were screened to exclude questionnaires with lower response quality such as repeated responses using the same IP address, choosing the same option for multiple consecutive questions, and short response time (i.e., <200 s). Prior to conducting data analysis, the reliability and validity of the questionnaire scales were assessed utilizing Cronbach's alpha via SPSS 26.0. Using Amos 28.0 software, a confirmative factor analysis was conducted to determine the factor structure of the PRS questionnaire. Factor loadings at each item should be greater than 0.40 and should average at least 0.70 at each construct.

The visual comfort assessment, acoustic environment assessment, and the Perceived Restorativeness Scale (PRS) were examined using the mean value of participants' ratings.

Independent two-sample *t*-tests were conducted to assess the differences between the sound group and the control group, as well as between the vision group and the control group, in response to Research Question I. In addition, a one-way ANOVA was performed to investigate the main effects of vision and sound, as well as their interaction effect, on restorative outcomes (Research Question II). If significant effects were identified in the ANOVA, post hoc tests using Bonferroni correction were conducted to examine specific group differences [60]. The significance level was set at 0.05. To assess whether participants'

perceptions varied across different groups, we analyzed and reported the mean differences (ΔM) between the experimental groups:

$$\Delta M = \text{Mean}(\text{Experiment group 1}) - \text{Mean}(\text{Experiment group 2})$$

4. Results

4.1. Participants Information

Out of 360 participants, a total of 360 valid questionnaires were collected. Each group comprised 30 participants, satisfying the minimum sample size required for statistical analysis [61]. Participants' demographic information is listed in Table 6. Among the respondents, 140 were male, representing 38.9%, while 220 were female, accounting for 61.1%. The majority of participants fell within the age range of 18 to 40 years, and most had attained a high school education. Additionally, a significant portion of the participants resided in urban areas, comprising 93.9%, indicating a notable level of familiarity with urban streetscape environments.

Table 6. Overall fit coefficient of PRS.

Category		Number	Percentage/%	Cumulated Percentage/%
Gender	Male	140	38.9	38.9
	Female	220	61.1	100.0
Age	18–30	189	52.5	52.5
	31–40	135	37.5	90.0
	41–50	17	4.7	94.7
	51–60	16	4.4	99.2
	Above 60	3	0.8	100.0
Education level	Junior school degree or equivalent	1	0.3	0.3
	High school degree or equivalent	13	3.9	3.9
	Bachelor's degree or equivalent	284	78.9	82.8
	Master's degree and above	62	17.2	100.0
Occupation	Student	87	24.2	24.2
	State-owned enterprises	38	10.6	34.7
	Public institution	42	11.7	46.4
	Civil servant	18	5.0	51.4
	Private enterprise	141	39.2	90.6
	Foreign company	24	6.7	97.2
	Freelancer	8	2.2	99.4
	Other	2	0.6	100.0
Living environments	Urban environments	338	93.9	93.9
	Rural environments	22	6.1	100.0

The validity of participants' answers was first examined. Cronbach's value for PRS was 0.968. Cronbach's α metrics for visual comfort of the four streets were 0.655, 0.842, 0.823, and 0.715; for the sound environment assessment, Cronbach's α = 0.842. Using Amos 28.0 software, confirmative factor analysis was conducted on the PRS questionnaire. The factor loading value for fascination, being away, compatibility, and extent dimensions were all above 0.7, which indicates the convergence validity was ideal, and the construct validity and convergence validity of the PRS used in this experiment reached the standard.

4.2. Research Question I: Can Vision and Sound Independently Enhance Restoration When Considering Different Street Types?

Among the four distinct streetscapes, both vision and sound groups exhibited enhancements in specific aspects of the restorative effects of these environments when compared to the control group (see Tables S2–S5 in Supplementary Materials).

For Taiping North Road, categorized as a traffic road, the sound group demonstrated a significant improvement in the greenness of visual comfort assessment ($p = 0.023$), acoustic environment assessment ($p < 0.001$, in all dimensions), and the PRS ($p < 0.001$, in all dimensions). Conversely, the vision group did not show significant changes in these three measurements.

For Zhujiang Road (living street), participants in the sound group reported significant increases in the pleasantness and quietness aspects of the acoustic environment assessment ($p < 0.001$), along with enhancements in the four dimensions of PRS ($p = 0.001$, $p < 0.001$, $p = 0.002$, and $p = 0.011$). In contrast, the vision group only exhibited significant differences in the visual comfort assessment related to green space ($p = 0.005$).

For Changjiang Road (comprehensive street), the sound group displayed significant differences from the control group, excelling in acoustic environment assessment ($p < 0.001$) and the PRS ($p < 0.001$). Additionally, it surpassed the control group in the dimensions of green space ($p = 0.006$) and street furniture ($p = 0.017$) within the visual comfort assessment. However, the vision group did not show any significant differences from the control group.

Finally, for Beiting Lane (service street), the sound group outperformed the control group in all aspects of visual comfort assessment, acoustic environment assessment, and PRS. In addition, the vision group indicated that enhancing the greenness of the streetscape could significantly improve the greenspace dimension of visual comfort assessment ($p = 0.048$), the quietness aspect of acoustic environment assessment ($p = 0.024$), and all dimensions of PRS ($p = 0.036$, 0.013, 0.020, 0.038, respectively).

4.3. Research Question II: Can the Combination of Vision and Sound Enhance Restorative Effects Compared to Their Independent Roles, When Considering Different Street Types?

The analysis presented in Table S6 of Supplementary Materials indicates that notable disparities exist among the four street groups regarding the greenness of visual environments, the pleasantness, quietness, and happiness associated with acoustic environment assessments and the PRS. Significant differences were observed between the sound group and the vision group, as well as between the vision group and the combination group. Conversely, no significant differences were identified between the sound group and the combination group.

For Taiping North Road, the sound group exhibited a notable increase in pleasantness ($p = 0.002$), quietness ($p = 0.01$), and appropriateness $p = 0.01$) when compared to the vision group in their assessment of the acoustic environment. Additionally, the sound group significantly outperformed the vision group in the PRS regarding attractiveness ($\Delta M = 3.83$, $p < 0.001$), being away ($\Delta M = 3.93$, $p < 0.001$), compatibility ($\Delta M = 3.90$, $p < 0.001$), and extent ($\Delta M = 4.47$, $p < 0.001$). Conversely, the combination group demonstrated a significant improvement in perceived restorativeness relative to the vision group, particularly in the greenness of visual environments ($\Delta M = 0.53$, $p = 0.02$), pleasantness ($\Delta M = 1.00$, $p = 0.02$), quietness ($\Delta M = 1.13$, $p = 0.01$), and appropriateness ($\Delta M = 1.13$, $p = 0.02$) of the acoustic environment. Furthermore, significant differences were also identified on the PRS between the vision group and combination group. However, no significant differences were observed between the sound group and combination group.

A comparable trend was noted for Zhujiang Road. In terms of alterations in green space, the combination group exhibited a significantly greater impact than the sound group ($\Delta M = 0.57$, $p = 0.04$). When assessing the acoustic environment, the sound group demonstrated a notable advantage over the vision group, with an estimated difference of 1.07 ($p = 0.004$) for the dimensions of pleasantness and quietness, and 0.93 ($p = 0.043$) for quietness. Additionally, significant disparities were identified between the combination group and the vision group, with differences of 1.40 ($p = 0.000$) and 1.37 ($p = 0.001$) in the pleasantness and quietness dimensions, respectively. Regarding the PRS evaluation, the

sound group surpassed the vision group in fascination and extent dimensions, while the combination group excelled over the vision group across all four dimensions of PRS.

For Changjiang Road, no significant differences were observed in the visual comfort assessment. However, notable differences emerged in the acoustic environment assessment and PRS. Specifically, the sound group significantly outperformed the vision group in the pleasantness and quietness dimensions, with p-values of <0.001, 0.007, and 0.021, respectively. In the PRS evaluation, the sound group also excelled over the vision group in fascination, being away, compatibility, and extent. Similarly, significant differences were noted between the combination group and the vision group, with the combination group outperforming the vision group in all aspects of the acoustic environment assessment and PRS. Nonetheless, no significant differences were found between the sound group and combination group.

For Beiting Lane, significant increasements were observed in the acoustic environment assessment in the sound group compared to the vision group as well as between the combination group and vision group. However, these metrics were not evident in the vision comfort assessment between the three groups. In terms of PRS evaluation, the sound group significantly outperformed the vision group in the pleasantness, fascination, compatibility, and extent dimensions, with p-values of 0.004, <0.001, 0.016, and 0.023, respectively. The combination group also significantly outperformed the vision group in all dimensions of the PRS evaluation. However, the difference between the combination group and sound group was not significant.

5. Discussion

5.1. The Independent Role of Vision and Sound

In this study, three dimensions of restorativeness evaluation were applied, including visual comfort assessment, acoustic environment assessment, and PRS. It is worth noting that both soundscape interventions alone and combined audiovisual interventions resulted in similar significant enhancements across three aspects of evaluations among the four streets. On the other hand, the visual interventions (enhanced GVI) had a limited effect on acoustic environment assessment and PRS evaluation. In other words, it seems that in the street-setting experiments, visual interventions (enhanced GVI) cannot independently exhibit a significant improvement on environmental perceptions, while audio intervention can.

In previous studies, it was believed that audio and visual perceptions are connected, where visual and audio factors tend to influence each other rather than in one direction [62]. It was confirmed that, in urban squares and parks, the relative visual elements, such as openness, greenspace, and spatial patterns, have key impacts on the acoustic comfort level, and adding natural sound sources such as water sounds and birdsong can lead to the enhancement of the visual comfort level [63–65]. However, street space is different from other open spaces, as users of street space mainly pass through it rather than stay in it for a long time. Perhaps because of this characteristic, changing the GVI had a limited effect on the overall environmental comfort.

Compared to the impact of visual intervention, in this study, the enhancement of auditory stimuli had a more significant positive effect on visual comfort. Similar findings have also been found in previous studies, indicating that most people's environmental perceptions are dominated by audio elements [66]. The reasons for this phenomenon may be explained by two points. On the one hand, traffic noise was found to be the most significant factor affecting environmental perception, so the birdsong added in this experiment may have had a masking effect on the traffic sounds, thus creating a more significant enhancement in environmental perception [42]. Other possible explanations could

be attributed to the manner in which visual stimuli are reproduced. Despite significant advancements in digital technology that have improved the immersive quality of digital research samples, accurately replicating the intricacies of real-world scenes continues to pose a challenge. Perhaps in digital research samples, changes in visual elements do not capture subjects' attention as much as audio elements do, causing visual elements to have an insignificant impact.

5.2. Audiovisual Interactions in Different Types of Streets

This study also highlighted the differences in environmental intervention effects due to varied street types, exploring four function types of streets—traffic, living, comprehensive, and service streets—according to *Nanjing Street Design Guidelines* [18]. These street types exhibit distinct functional purposes, which influence the types of activities they support, as categorized by Gehl: necessary, optional, and social activities [30].

For example, Taiping North Road exemplifies integrated urban design, where there is the coexistence of green infrastructure and public facilitates, both necessary and optional activities. In contrast, Zhujiang Road, a commercial-residential hybrid area, primarily supports necessary activities like grocery shopping and commuting, with occasional optional activities such as informal conversations or leisurely strolls. Changjiang Road, adjacent to government offices, is dominated by necessary activities related to official business, with its formal setting limiting opportunities for optional or social interactions. Beiting Lane, however, stands out with its narrow width and wall murals, creating an environment conducive to optional and social activities.

The initial green view index (GVI) of the four streets further highlights their differences (Table 2). Taiping North Street ranked the highest, with an average GVI of 25.96%, followed by Changjiang Road with 18.48%. Previous studies indicated that when the GVI reached around 25%, the effect from greenery started to level off [67,68]. In other words, the lack of improvement effect on these two streets after the increase in GVI was perhaps due to the fact that their initial GVI had already reached a considerably high level. In contrast, the improvement effect from green visibility was only seen in Beiting Lane, where both audio and audiovisual interventions have shown significant impacts on Beiting Lane compared to the other streets. This can be attributed to its unique characteristics, such as existence of murals (refer to Table S1 in the Supplementary Materials) and a height-to-width ratio nearing 1 [44,69], which may have enhanced the effectiveness of visual and sound interventions. These features align with Gehl's concept of optional and social activities [30], where aesthetic and environmental qualities play a crucial role in encouraging user engagement.

Statistical analysis (e.g., ANOVA) revealed that the impact of auditory, visual, and audiovisual elements did not significantly differ across street types. However, the sound group and the combination group outperformed the vision group, while no significant difference was observed between the sound group and the combination group. These findings underscore the importance of prioritizing soundscape design in urban planning to enhance environmental quality and user experience, particularly in streets where optional and social activities are encouraged.

5.3. Theoretical and Practical Contributions

Prior studies have predominantly examined the visual or auditory aspects of perceived restorativeness in isolation. Our research introduces a multi-sensory framework that integrates time-series street view images (e.g., extracting GVI) with on-site acoustic recordings (e.g., measuring sound pressure levels and implementing natural sound sources). Using a randomized controlled experiment with a control group and three sensory-adjusted groups,

we examined the independent and interactive effects of vision and sound on the perceived restorativeness of streetscapes, considering street type variations. This contribution introduces a novel multi-sensory perspective to the existing research on restorative landscape.

This research also provides implications for planning practices. In this study, audio intervention has a more significant impact on the overall environmental perception, compared to visual intervention. This suggests that future street design and regeneration should consider enhancing environmental quality from the perspective of soundscape design. The concept of soundscape intervention aims to improve the composition of sound sources and sound perceptions by employing spatial, landscape, and environmental design at various scales. There are two primary approaches to soundscape intervention design: the introduction of positive sound sources or the masking of noise [70,71]. The results of this study support a dual strategy for soundscape optimization in future urban street design and regeneration:

Macro-scale and long-term strategy—ecological soundscape development: This involves systematically enhancing the street's bio-acoustic potential through biodiversity-focused plant and waterscape design (e.g., increasing avian soundscape richness by adding broadleaf canopy coverage; implementing cascading water features that produce broadband masking effects across the 200–5000 Hz range), thereby establishing spatiotemporally continuous natural sound matrices [36,72].

Micro-scale and short-term strategy—psychoacoustic intervention: Since traffic noise poses the primary threat to street soundscapes, its impact can be mitigated by combining positive sound masking (e.g., deploying speakers that release white noise, integrated into smart lighting systems to mask traffic noise based on its patterns) with cognitive diversion techniques (e.g., embedding music or culturally significant auditory cues to shift attention) [73]. The guidelines for enhancing street soundscapes are context specific. For instance, in living streets, where tranquility and community are prioritized, the incorporation of bird calls or rustling leaves can add a calming sense. On comprehensive streets, where a variety of activities occur, the use of water features combined with soft background music or auditory cues that resonate with the local culture can create a more pleasant auditory environment.

On the visual side, the effectiveness of enhancing GVI in different streets depends on the streets' initial conditions and types. These results support policies such as integrating thresholds in GVI. For streets with low initial GVI, planners should prioritize integrating green resources to maximizing the restorativeness effect, e.g., by cultivating plants with expansive canopies in limited spaces and integrating vertical greenery systems, to enhance the green view ratio from perceptual aspect, thereby maximizing the restorative benefits of green landscapes. For streets with already high GVI, the impact of further increasing greenness is limited. Therefore, planners should consider the influence of other factors such as spatial parameters, plant species diversity, color schemes, and layout to achieve further improvements in visual appeal and functionality. While this study offers valuable insights for urban design practice, it captures only a portion of the complex factors shaping streetscape perception. Effective landscape design must integrate diverse considerations—from environmental characteristics and human spatial behavior to ecological sustainability and cultural significance—to achieve truly livable, high-quality urban spaces.

6. Conclusions

Streets occupy a high percentage of urban public space and play a vital role in restorativeness. Prior research has primarily examined the independent effects of vision on perceived restorativeness, with few research endeavors into the independent and interactive effects of sound and vision on the public perception of restorativeness. Using a

randomized controlled experiment with a control group and three sensory-adjusted groups, we looked into the effect of four different types of streets: living, traffic, comprehensive, and service streets. It was found that interaction effects of vision and sound contributed to enhanced perceived restorativeness. Sound contributed to better restorative effects compared to vision, while the differences between the sound and combination groups were not significant. The research findings highlight introducing positive sound sources or enhancing the masking effect of soundscape in street environmental design.

This study has limitations in terms of the following aspects: Firstly, the limited sample size and control over variables prevented the inclusion of additional visual and auditory variables across various groups. Future research should expand the scope by integrating a wider range of interrelated variables—such as street spatial morphology, visual exposure diversity, and sound pressure levels—to more comprehensively assess the complexity of streetscape perception. Secondly, the experiments were conducted through online recruitment, which introduces the potential for participants to experience slight differences in screen resolution, which could impact the findings. Future research could address these limitations and might consider the use of wearable technology and ergonomic assessments to more precisely measure participants' responses to diverse stimuli. Thirdly, our participant pool (predominantly 18–40 years) may limit generalizability due to age-related differences in mobility and perception. The online format could further exacerbate this through digital divide effects. Future studies should employ age-stratified sampling with adaptive methods (e.g., voice-assisted surveys) to better capture perspectives of the elderly.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land14040757/s1: Table S1: Links to street panoramic roaming scenes; Table S2: Taiping North Road statistical analysis; Table S3: Zhujiang Road statistical analysis; Table S4: Changjiang Road statistical analysis; Table S5: Beiting Lane statistical analysis; Table S6: Post hoc analysis of different restorativeness measurements between sound, vision, and combination groups.

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Visualising and Valuing Urban Agriculture for Land Use Planning: A Critical GIS Analysis of Sydney and Neighbouring Regions

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Abstract: The loss of a city's agricultural lands due to land use change through urban development is a global problem, as local food production is an essential green infrastructure for intergenerational sustainability. Like many cities, much of Sydney's rapid urban development occurs on land previously used for food production. Sydney has one of the highest rates of urban growth among Western cities and a planning strategy that marginalises its agricultural productivity. To better understand and advocate for Sydney's capacity for food production we explore all available government datasets containing agricultural biophysical capacity using a critical GIS approach. Employing various spatial-data visualisations to contextualise agricultural production, we examine inherent biophysical agricultural capacity in Sydney and comparable regions along the eastern coast of NSW. Our approach interrogates the notion that Sydney's metropolitan landscape is of low inherent biophysical quality for agriculture, thereby challenging current development and planning orthodoxy and policy. In ascertaining Sydney's comparative capacity for agriculture we find that, despite current metropolitan planning policy, datasets reveal western Sydney is biophysically well suited for agriculture. Sydney overall is comparable to five of six other coastal regions of NSW and superior to at least two. While acknowledging metropolitan land use complexities that shape agricultural production in practice, we argue for improved critical application and contextual understanding of existing agricultural datasets to better inform future planning policy to advance regional food security and aid long-term sustainability.

Keywords: critical GIS; urban development; peri-urban agriculture; land use change; green infrastructure; open data; local food supply; food security; food production; landscape planning

1. Introduction

Food production in direct proximity to urban populations—herein urban agriculture [1]—is an essential green infrastructure and vital living system helping underpin intergenerational sustainability, food supply security and regulating life support ecosystem services [1–4]. The ongoing loss of peri-urban agricultural landscapes from urban development represents a critical challenge for urban sustainability and metropolitan planning worldwide [5–8]. As urban areas increase their population and physical footprints, they regularly encroach on agricultural lands adjacent to or interspersed within metropolitan regions [9,10]. Within urban contexts, agricultural land is frequently evaluated using short-term perspectives and a focus on potential quick financial returns from

residential subdivisions and associated land uses. Land speculation ahead of residential, industrial, and mixed-use subdivisions can trigger a holding pattern causing agricultural land to fall fallow [11] resulting in an accelerated process that strips agricultural capacity from cities. The prioritisation of short-term economic gains over long term sustainability can serve to justify the rezoning of urban agricultural land for urban development [12]. This phenomenon, sometimes understood through the lens of "urban growth machine" theory [13,14], posits that various stakeholders, including developers, state and local governments, and consultants, form coalitions to prioritise immediate economic gains, often at the expense of long-term sustainability and the intrinsic value of land uses such as urban agriculture.

If left unchecked, urban economies that inherently rely on global investment, construction, and housing development can become trapped in a pattern of short-term economic activities, generated through property development and supply chains involving significant material use in construction sectors [15,16]. Moreover, globalisation and neo-liberal capital flows exacerbate this trend, with policymakers catering to related financial economic pressures rather than local sustainable developmental goals [17,18]. In the urban growth machine model, professional consultants generate narratives "across places that can mistakenly be taken as evidence of economic necessity" [13]. Such narratives can promote the conversion of agricultural land for urban uses, undermining the critical role that such land plays in food security and environmental health [19,20].

In this paper, we analyse Sydney within this theoretical context. In doing so, we dispute the constructed notion that Sydney's metropolitan landscape is biophysically unsuited to agriculture, thereby challenging current planning orthodoxy. To do this we ask the question "what is Sydney's inherent biophysical capacity for agriculture?". Our paper seeks to answer this by utilising a Critical Geographic Information System (Critical GIS) approach [21], in which we use the best available datasets and present them for quantitative and qualitative evaluation using spatial comparisons, graphs, and a range of visual techniques. By considering inherent soil fertility and agricultural capacity, alongside questions of urban governance, we explore how these underappreciated factors interact to present a more constructive and balanced narrative around metropolitan agriculture in Sydney and its surrounding coastal regions.

The paper is structured according to four subsequent sections. The Background provides an outline of the history and planning of Sydney with respect to urban agriculture. The Methods and Materials Section outlines the approach to determining boundary areas for Sydney and the six comparison cases, as well as datasets used, and analyses completed. The Results Section visually presents the mapping and data generated, based on seven case regions, two boundary methods, four datasets, and visual results. The Discussion critically unpacks the implications of our visual results relating to Sydney's metropolitan planning, sustainability policy, and regional identities. The Conclusion summarises the novelty and significance of findings for Sydney, NSW, and more widely. By demonstrating how agriculture can be broadly analysed and compared, we aim to generate discussion on this marginalised system as an integral component of sustainable urban planning and food supply security.

2. Background

Sydney is one of the fastest growing urban regions in the Western world and faces many of the pressures described using the growth machine theory [22,23]. Within the city, a combination of rapid urban growth and weak protections for agricultural land uses continues to place extreme pressure on metropolitan agricultural production [24,25]. Agriculture has been an integral part of Sydney's history, stretching back to Indigenous roots and early

colonial days and continuing throughout the twentieth century [26–29]. It has therefore contributed significantly to the city's success and cultural identity. However, agriculture has also been entangled in a culture of financial speculation and has faced challenges due to tensions with alternative land uses such as housing [22]. While some planners and urban visionaries have portrayed this shift as inevitable [30], it has been forcibly shaped by concrete planning policies and methods that have not prioritised agriculture in the same manner as housing, transportation, and a range of other land uses [31]. Consequently, agriculture has not been recognised as a vital "city system" within the planning of the urban future of Sydney [22,32].

Since 1948, nine metropolitan-scale planning strategies have been produced to guide Sydney's development and all of them have intentionally or inadvertently marginalised agriculture. Zeunert and Freestone published a recent analysis of the nine plans based on their integration of agriculture and found that each planning vision offered urban agriculture "lip service at best, and complete disregard at worst" [32] (p. 247). Other researchers, such as Budge [33], have noted the marginalisation and disregard for urban agriculture in specific metropolitan plans, pointing to a range of factors driving the erosion of agriculture including urban growth 'planned' on key intensive food production lands [34]; suggestions that conversion of agriculture is necessary and inevitable [35]; highly variable engagement between planning and the agricultural sector [35]; tensions between state and local government perspectives [25]; corruption in political-planning processes involving rezoning of important agricultural lands [36]; and, conflicts between top-down and bottom-up agricultural land protection policies and practices [31].

Planning policy in Sydney has historically favoured developers, with urban development following short-term financial drivers rather than principles of sustainability, resilience, and health [22]. Sydney's development history is replete with examples of pro-development scandals and biassed planning policies [37,38]. Within this context, urban agriculture has been characterised as unviable and of marginal use so much so that planning officials have suggested "there is no place for agriculture in the Sydney region. Agriculture belongs over the Great Dividing Range, and any agricultural land in Sydney is land awaiting higher economic development" [11]. This perspective reflects a broader trend in Sydney, where market-driven determinants have facilitated the conversion of agricultural land to what is deemed 'higher and better uses' [33,39]. In this context, land is often viewed as 'suburbs in waiting' [35], reinforcing the notion that agricultural spaces are expendable in favour of urban expansion. This phenomenon mirrors prevalent global patterns of embedded power, governance, and capital systems that are oriented toward urban property development [40]. The implications of such a planning paradigm are significant, as they not only undermine the potential contributions of urban agriculture to food security and community resilience but also perpetuate a cycle of unsustainable urban growth.

Sydney's ninth and most recent metropolitan plan, *A Metropolis of Three Cities*, and its associated district plans were released by the Greater Sydney Commission in 2018 [30] (herein GSC, which was recast as the 'Greater Cities Commission' in late 2021). Zeunert and Freestone [32] (p. 267) characterised the GSC's strategy as a "supercharged" neoliberal approach to land use and development, accelerating the trajectories of the eight prior metropolitan plans. The 2018 strategy's rapid population growth necessitates substantial urban development: 725,000 new dwellings by 2036 [30]. The report claims "little change in [Sydney's] outward spread" will result [30] (p. 31). This is despite specifying that 81% [41] of the earmarked 184,500 dwellings for the 'Western City District' will be detached housing [30] (p. 62). Recent spatial-mapping of Sydney's development counters this claim,

demonstrating the city's continued outward spread, with agriculture as the primary land use disappearing under urban development [22].

Prior to their release of *A Metropolis of Three Cities*, the GSC commissioned a study titled *Values of the Metropolitan Rural Area of the Greater Sydney Region* [19]. This report presented twelve 'values' for consideration in Sydney's metropolitan land use planning, including *agriculture; biodiversity; water quality; air quality; mining and extractive industries; scenic landscape values; tourism and recreation; waste management; rural lifestyle; rural towns and villages; European and Aboriginal Heritage*; and '*Other*'. The report also divided Greater Sydney into five districts, each examined across the following: *agriculture; biodiversity; water quality; mining and extractive industries; landscapes; tourism*; and '*Other*' values. The study's agricultural analysis utilised Land and Soil Capability (LSC) and Biophysical Strategic Agricultural Land (BSAL) datasets (two of the four used in this study) to present its spatial and statistical assessment of Sydney's inherent soil capacity and agricultural industry. Clarke's [19] analysis of Sydney evaluated agriculture in relation to short-term economic considerations, utilising the term 'market (e.g., market forces, market value) in economic contexts 35 times. However, similar consideration is not given to the other 11 urban values which include biodiversity, scenic landscape values, tourism, and recreation or heritage. This one-eyed planning assessment of agriculture is consistent with the way this system has been treated in consecutive policies and plans.

Our paper therefore addresses this oversight, with regard to metropolitan agriculture, to consider it using a broader, analytic contextual lens.

3. Materials and Methods

In this paper we reflect on how urban agriculture has been diminished by uncritical mainstream Sydney planning establishment, and to do this, we apply a critical GIS method. Rather than applying spatial mapping practices to reveal a single definitive answer to the question "what is Sydney's inherent capacity for urban agriculture?", we use critical GIS approaches to expand current siloed thinking to catalyse debate and draw "new lines" and connections, as GIS scholar Wilson might say [42]. Unlike conventional geographic information systems that treat spatial data as objective and neutral, critical GIS recognises input mapping and data as deeply contextual and inherently political processes [43,44]. By interrogating how spatial information is created and represented, critical GIS reveals how conventional mapping techniques can reproduce existing social hierarchies and power structures.

Critical GIS methodologies challenge what Pavlovskaya [21,45] identifies as the problematic "always-assumed alignment of GIS with quantitative research". Instead, it uncovers deeper historical processes, power dynamics, and development patterns that shape contemporary landscapes, while embracing both qualitative and quantitative methods. This hybrid approach transforms maps from passive documents into dynamic tools for understanding historical spatial political relationships, social justice, and community empowerment, ultimately helping researchers and planners develop more equitable and contextually sensitive strategies for spatial development [46]. In our case, we make what has been invisible visible, representing existing data to shape conversations on urban agriculture as a valuable system in our cities.

Our research builds upon Clarke's [19] 2017 Greater Sydney Commission study which also uses agricultural datasets to assess Sydney's inherent land capacity for agricultural production. However, unlike Clarke et al., we contextualise and compare our study of Sydney with other relevant urban regions along the coast of NSW. We also draw on more diverse datasets and apply a greater range of analyses.

3.1. Defining and Questioning Spatial Frameworks: What's in a Boundary?

To analyse a region's agricultural capacity, a bounded spatial area is helpful and, in many respects, essential. The boundary area or footprint can have a significant influence on the results of the analysis and provoke alternative insights depending on how it is drawn. In relation to the agricultural landscape and urban definition of Sydney, widely varying boundaries have been used and referred to in the literature [22]. To interrogate this variation, we completed a sieve mapping exercise [47] overlaying and comparing ten historical boundaries that have previously been used to describe the extent of 'Sydney' or 'Sydney Basin' in the agricultural and metropolitan planning literature (Figure 1). These vary in size, by as much as 17.5 times.

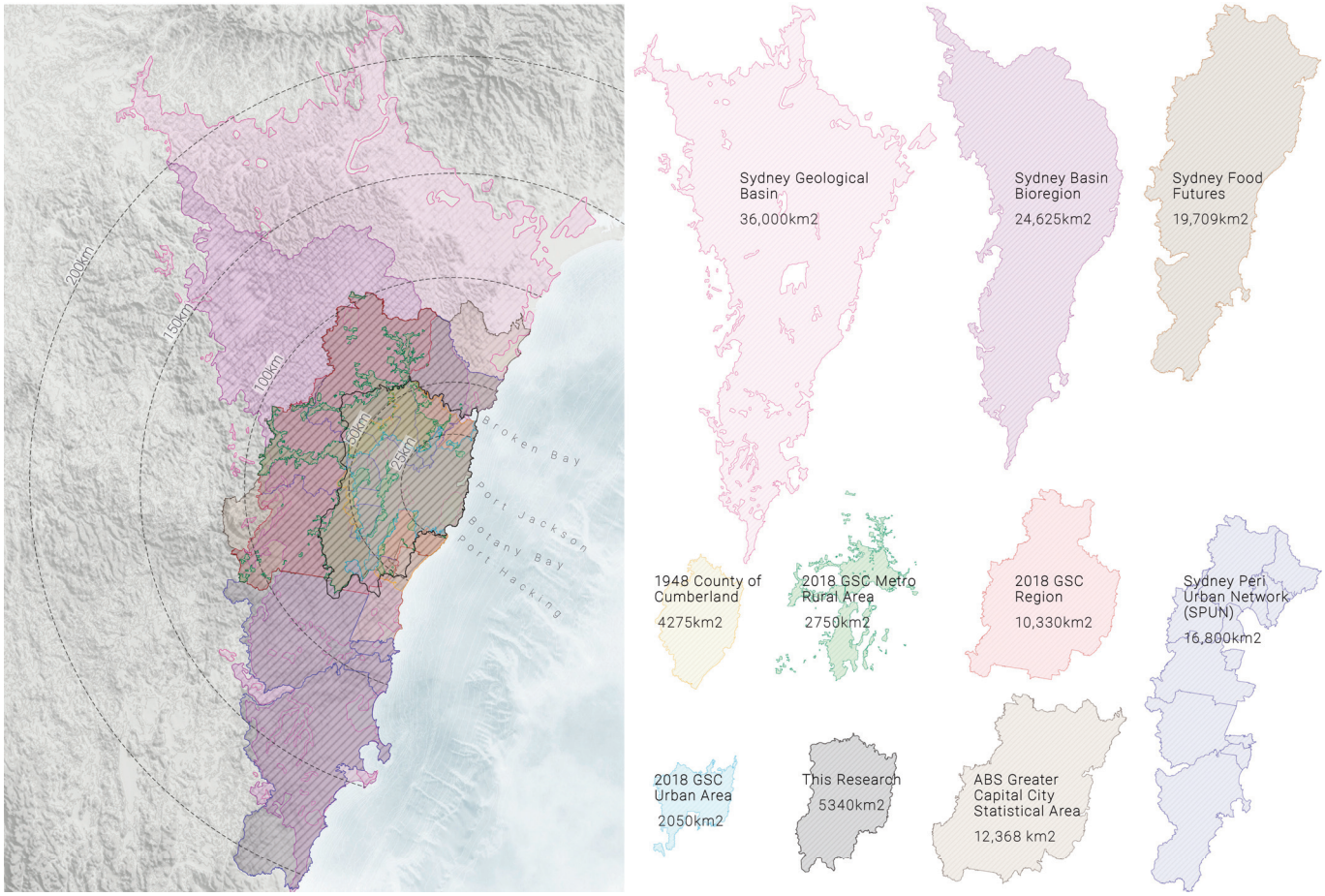


Figure 1. Varying boundaries termed 'Sydney' or 'Sydney Basin' in the agricultural and planning literature, largest to smallest: Sydney Geological Terrestrial Basin (36,000 km^2) [48]; Sydney Basin Bioregion (24,625 km^2); Sydney's Food Futures (19,709 km^2) [22,49]; Sydney Peri Urban Network (16,800) [22]; ABS Greater Capital City Statistical Area (12,368 km^2) [50]; 2018 GSC Region Boundary (10,330 km^2) [30]; 'this research' (adapted from Zeunert & Daroy [22], see Figure 2) (5340 km^2); 1948 County of Cumberland (4275 km^2) [51]; 2018 GSC Metro Rural Area (2750 km^2) [30]; and, 2018 GSC Urban Area (2050 km^2) [30]. Figure by Stephanie Stankiewicz, Josh Gowers, and Joshua Zeunert. Data Sources: Australian and NSW Government and the agencies and authors noted in the caption.

Whilst all boundaries have their utility, for our research, we select the boundary of 5340 km^2 used by Zeunert and Daroy [22] (Figure 2). We employ this for its usefulness in capturing Sydney's existing agricultural areas and metropolitan municipalities (local government areas) without overreaching into neighbouring urban centres Wollongong and Newcastle (and beyond)—an issue with most boundaries shown in Figure 1. Our selected

area and boundary relate to Sydney's topography, which has been shaped over geological time scales by water catchments and incised river valleys and is bordered by the Pacific Ocean. Although Sydney's built form and population continue their considerable growth, its metropolitan context and local agricultural capacity remain defined and constrained by prominent geographic barriers of sandstone geology, topography, rivers, and coastline, and these are encompassed by Zeunert and Daroy's boundary [22].

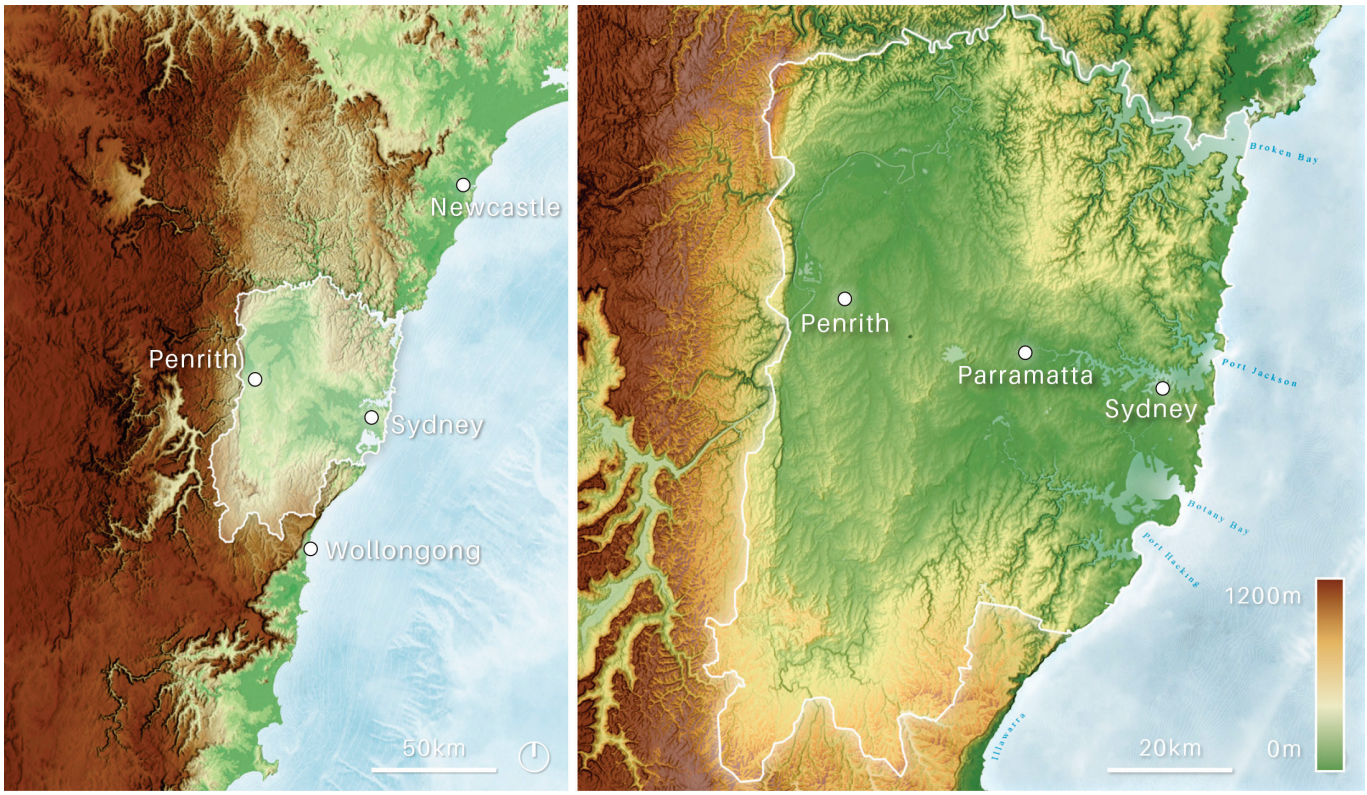


Figure 2. Sydney's boundary area of 5340 km^2 (in white, **left** and enlarged, **right**) used in this study (adapted from Zeunert and Daroy [22]). The wider context (**left**) shows how Sydney's 'basin' is encircled by topographic and hydrological barriers. This greatly limits where agriculture can be practised in direct proximity to Sydney. Data sources: NSW Foundation Spatial Data Framework: Elevation and Depth Theme, and the Australian Bathymetry and Topography Grid, 2009. Figure by: Josh Gowers and Joshua Zeunert.

3.2. Selecting Neighbouring Agricultural Regions as Comparison Cases

To gain a better understanding of Sydney's inherent capacity for agriculture, six regions have been selected as comparison cases with Sydney. Our seven cases were visualised and analysed with respect to their agricultural capacity. This approach revealed the variation in agricultural capacity along the coastal region of NSW. Selected regions were all within the State of NSW for reasons of dataset availability and consistency. In selecting comparison cases, we sought geographic areas with broadly similar characteristics to Sydney. We used four criteria to select the case studies. Our criteria included coastal proximity and climate, presence of distinct local government areas, river(s) within catchment systems, and landforms including gradients permitting agricultural activities.

Based on these criteria, we selected the seven regions (Table 1) that between them provide a relatively even sampling of agricultural areas along the eastern seaboard of NSW. Cases spanned this region from north (near the Queensland border) to south (the Victorian border) and included the Byron; Coffs; Port Macquarie; Lower Hunter; Sydney; Shoalhaven; and Bega agricultural regions (Figure 3).

Table 1. Areas in square kilometres for the seven sites for both methods of boundary determination.

Region	Method 1 Sydney Boundary (km^2)	Method 2 LGA Boundary (km^2)
Byron	5293	2142
Coffs	5297	3983
Port Macquarie	5275	3443
Lower Hunter	5012	3885
Sydney	5340	5340
Nowra	4974	4696
Bega	5318	6313
MEAN	5215	4258

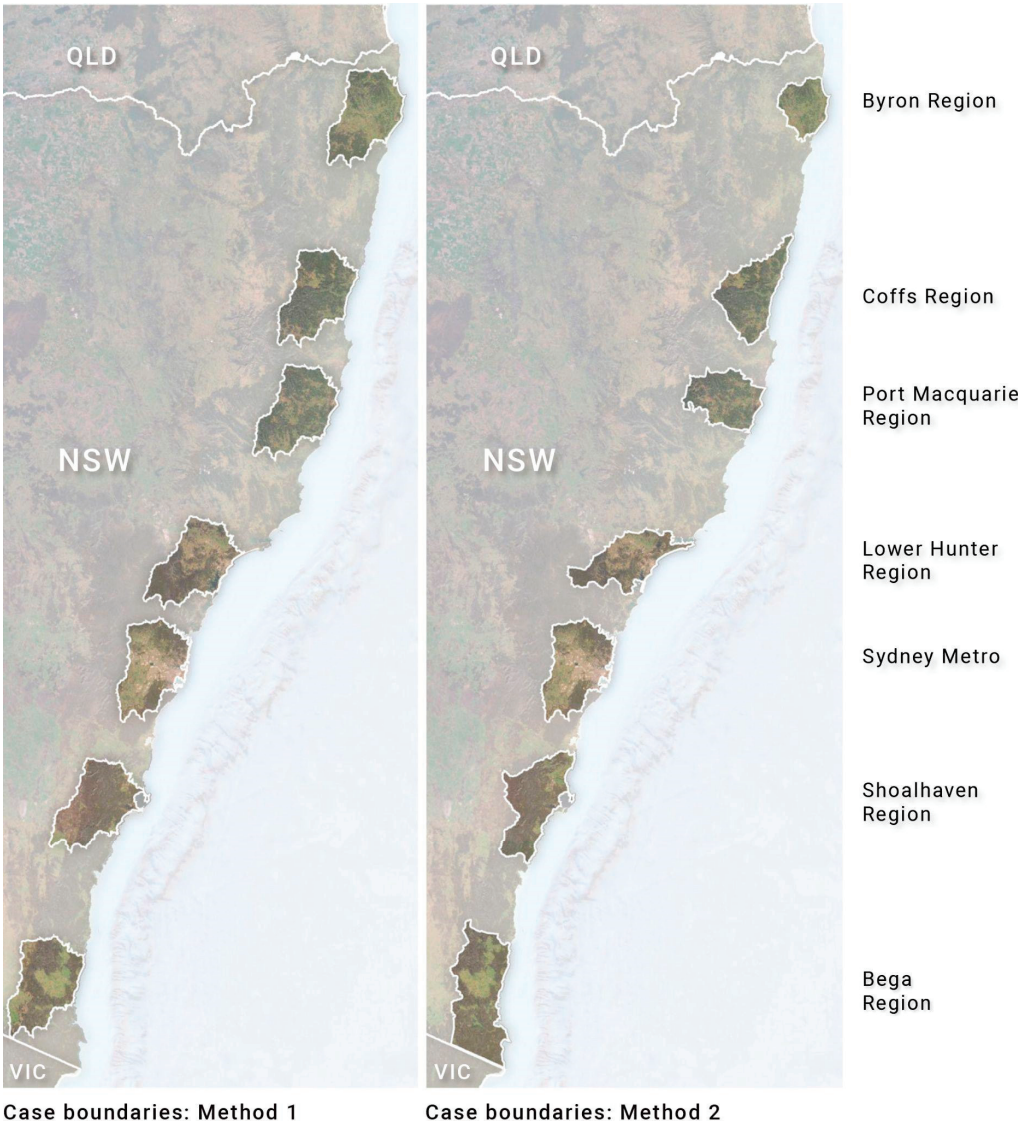


Figure 3. Sydney and six comparison sites. Method 1, (**left**), applies Sydney's boundary area to each site, adjusting only for the coastline. Method 2, (**right**), utilises an identical approach for all cases using local government areas, topographic and water catchment analysis, and state boundaries. Figure by Josh Gowers and Joshua Zeunert.

3.3. Approaches to Evaluate the Seven Regions and Their Agricultural Capacity

Drawing on critical GIS theory, we completed an exploratory spatial analysis through the application of two distinct footprints. Drawing inspiration from visual analytic land-

scape architecture approaches, particularly the work of Weller and Bolleter [52], the method superimposes standardised footprints or Areas of Interest (AOIs) across different coastal contexts to reveal spatial relationships and patterns that might otherwise remain hidden. The dual-footprint approach, combining what we term method 1 and method 2, enables alternative visualisation and analysis of the datasets, creating opportunities for comparative spatial investigation and reflection.

Method 1 superimposes the Sydney Metropolitan Boundary defined by Zeunert and Daroy [22] (Figure 2) as a repeated unit of analysis, adjusted only for each individual case's coastline to exclude the ocean. Method 2 individually applies the technique used to determine Sydney's boundary. Namely, it accounts for the nexus of political boundaries of the Local and State Government Areas [50] with local topographic conditions, water catchments, and drainage basins.

Rather than pursuing definitive conclusions, this methodology serves as a generative analytical tool that promotes critical engagement with spatial data. By maintaining consistent boundary extents and methods across different case regions, our approach facilitates the direct comparison of spatial qualities, scale relationships, and morphological characteristics. This comparative framework allows researchers to challenge conventional interpretations of urban form and spatial relationships.

3.4. Datasets Used in the Study

Four official agricultural datasets with sufficient spatial coverage were used in this research and these are listed in Table 2 and visualised in Figure 4. These are: *Land and Soil Capability* (LSC); *Inherent Soil Fertility* (ISF); *Biophysical Strategic Agricultural Land* (BSAL); and (draft) *State Significant Agricultural Land* (SSAL). These are the only viable datasets for comparing urbanised regions' biophysically inherent agricultural capacity in NSW. LSC and ISF classify for the entire spatial extent of metropolitan Sydney and NSW (i.e., polygons providing full state land-area coverage), whereas BSAL and SSAL provide statewide coverage identifying only agriculturally significant land patches (isolated polygons). The SSAL dataset is currently in a draft state (and has been for around four years) but is useful as a comparative dataset. Datasets that did not provide sufficient coverage were excluded from the study. Each dataset was used to independently analyse all seven case studies. The four datasets were therefore applied to present four independent sets of analysis. These were the most recent datasets and all remained relevant and available as open data as suggested by their accompanying data quality statements. The four datasets use different classification approaches and convey different types of information. Their key distinctions are as follows:

- Classification approach (gradient vs. binary);
- Specific criteria emphasised (limitations, fertility, and productivity);
- Development stage (established vs. draft);
- Selectivity (comprehensive classification vs. identification of only the highest value lands);

It is important to note that LSC, ISF, and BSAL use only biophysical data, such as soil, climate, or topography, and exclude economic and social data [53]. This aligns with our research aim of ascertaining and comparing inherent capacity only. Later in the discussion we suggest areas for further research incorporating social, economic, and infrastructural data outside the scope of this study. Our approach and method follow similar studies by others [54–56].

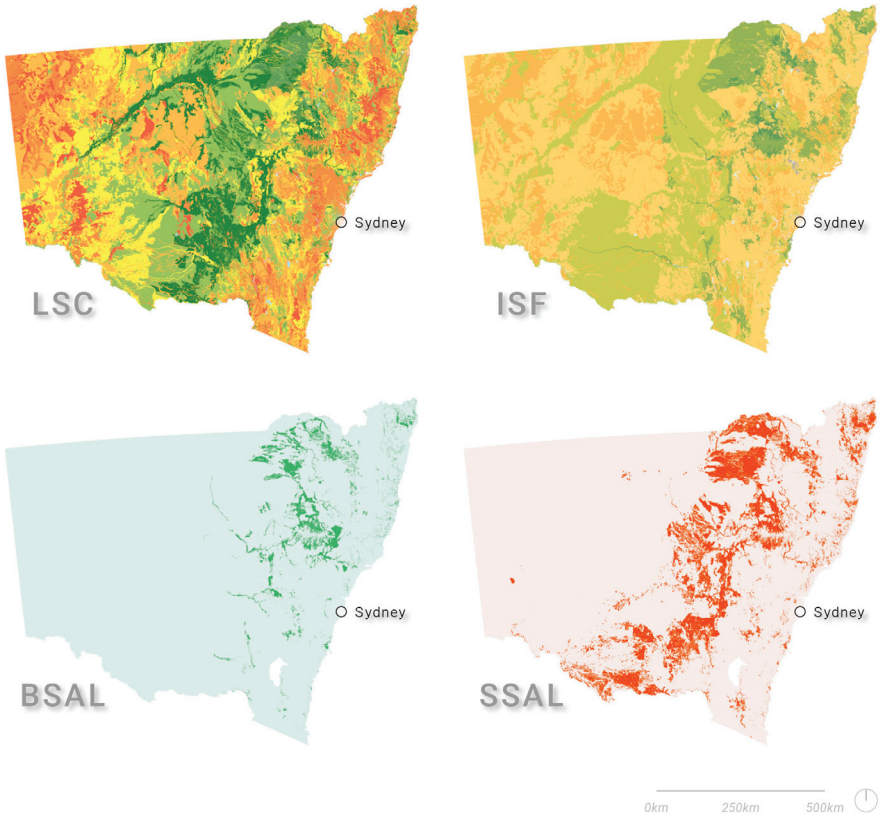


Figure 4. The four NSW agricultural datasets that provide data covering metropolitan Sydney and all of NSW: LSC, ISF, BSAL, and (draft) SSAL. LSC and ISF colour codes are shown in subsequent Figures 5–8 and Tables 3–6. Figure by Josh Gowers and Joshua Zeunert. Data sources: NSW Government noted in Table 2.

Table 2. Datasets used in this study.

Dataset Name and Year Published	Classes	Notes
LSC: Land and Soil Capability Mapping for NSW [57] 2008. Revised 2021	1—Very slight to negligible limitations 2—Slight but significant limitations 3—Moderate limitations 4—Moderate to severe limitations 5—Severe limitations 6—Very severe limitations 7—Extremely severe limitations 8—Extreme limitations	**Land and Soil Capability (LSC)** provides a comprehensive eight-class assessment system that evaluates land based on its capacity to sustain agricultural activities without degradation. The classification explicitly measures limitations, with Class 1 lands having minimal limitations (suitable for intensive agriculture) and Class 8 lands having extreme limitations (suitable only for conservation).
ISF: Estimated Inherent Soil Fertility of NSW [53] 2013. Revised 2021	1—Low 2—Moderately low 3—Moderate 4—Moderately high 5—High	**Inherent Soil Fertility (ISF)** utilises a five-class system focusing specifically on the natural fertility of soils in NSW. This dataset was developed using the same baseline soil mapping as LSC but focuses exclusively on soil fertility rather than overall land capability. The classification ranges from low (1) to high (5) fertility.
BSAL: Biophysical Strategic Agricultural Land [58] 2013	1—Biophysical Strategic Agricultural Land	**Biophysical Strategic Agricultural Land (BSAL**) employs a binary classification system (BSAL or non-BSAL). Unlike the other datasets, BSAL identifies only lands that meet specific criteria for high agricultural productivity, considering soil quality, water resources, and landforms. BSAL represents the most selective classification, identifying only lands capable of "sustaining high levels of productivity with minimal management practices".
SSAL: Draft State Significant Agricultural Land [59] 2021	1—State Significant Agricultural Land	**State Significant Agricultural Land (SSAL)** also uses a binary classification system but is still in draft form. SSAL builds upon previous datasets but includes additional considerations for identifying the "best agricultural lands". Unlike the other datasets, SSAL is explicitly noted as preliminary, with acknowledgment of data constraints and variable quality.

3.5. Data Processessing and Visual Analyses

Data preparation was completed by clipping the four datasets for the seven cases and the two boundaries for each case in ArcGIS Desktop (ArcMap) (10.8.2). This generated

forty-two maps (BSAL and SSAL analyses for the two boundary conditions were completed on the same map). The results are tabulated and displayed as vertical bar graphs (total land in km^2 for each classification) for all comparison maps using Adobe Illustrator 2023 and Adobe Photoshop desktop (version 24.5), also presented in tables. For the LSC and ISF, the results are also shown as proportions (percentages of each ranking of the total boundary area) in pie charts (%) and these are ranked out of seven (according to the seven cases examined), with 1 being the greatest proportion of land area and 7 the least.

The pie charts describing percentages (rather than the total land area) are used to communicate the ratio of land suitable for agriculture in each study region. The vertical bar graphs do not account for boundary variations between the cases; rather, they convey the total land area (km^2) in each ranking for an individual region and dataset in isolation. Pie charts are not used for BSAL and SSAL as these datasets consist of one class only. The visual maps and graphs are set out to provide an accessible understanding of the distribution and quantity of agricultural lands described within each dataset in relation to the seven regions.

4. Results

Four sets of analyses, one for each agricultural dataset, were completed, and these are presented below. The first dataset visualised was Land and Soil Capability (LSC) [57] and this is shown in Figure 5 (Method 1) and Figure 6 (Method 2) and Table 3 (Method 1) and Table 4 (Method 2).

The second dataset visualised is the Estimated Inherent Soil Fertility of NSW (ISF) [53] and this is shown in Figure 7 (Method 1) and Figure 8 (Method 2) and Table 5 (Method 1) and Table 6 (Method 2).

The Biophysical Strategic Agricultural Land (BSAL) results are shown in Figure 9 and Table 7, with both Methods' areas shown concurrently (Method 1—red, Method 2—blue). Similarly, the State Significant Agricultural Land (SSAL) results are shown in Figure 10 and Table 8.

Table 3. Land Soil and Capability results for Method 1's boundaries by region (and NSW total). Each region shows three rows of data: land area for each class of land (1–8) in km^2; the percentage of each class within the total area of each region (km^2); and comparative rankings/7 for each region based on the percentages. Class colours correlate across all LSC figures and tables.

Class/Case	Best 1	2	3	4	5	6	7	(Worst) 8	Total km^2
Byron (km^2)	0	0	1156	1013	357	1386	991	372	4119
%	0%	0%	21.9%	19.2%	6.8%	26.3%	18.8%	7.1%	100%
Rank/7			1	3	6	2	6	5	
Coffs	0	0	256	818	662	692	1290	1572	5034
%	0%	0%	4.8%	15.5%	12.5%	13.1%	24.4%	29.7%	100%
Rank/7			3	4	4	5	5	1	
P. Macquarie	0	0	376	592	252	1363	1362	1311	4880
%	0%	0%	7.2%	11.3%	4.8%	25.9%	25.9%	24.9%	100%
Rank/7			2	5	7	3	4	2	
L. Hunter	0	0	241	1255	820	645	1860	112	4693
%	0%	0%	4.9%	25.4%	16.6%	13.1%	37.7%	2.3%	100%
Rank/7			4	2	2	7	1	6	
Sydney	0	0	115	2046	483	674	1556	75	4834
%	0%	0%	2.3%	41.3%	9.8%	13.6%	31.4%	1.5%	100%
Rank/7			6	1	5	6	3	7	
Shoalhaven	0	0	167	541	678	1323	1696	534	4772
%	0%	0%	3.4%	11.0%	13.7%	26.8%	34.3%	10.8%	100%
Rank/7			7	6	3	4	2	4	
Bega	0	0	56	358	1552	1590	882	872	5254
%	0%	0%	1.1%	6.7%	29.2%	30.0%	16.6%	16.4%	100%
Rank/7			7	7	1	1	7	3	
NSW	0	14,659	116,025	190,846	154,928	174,023	108,783	48,889	677,469
%	0%	1.8%	14.4%	23.6%	19.2%	21.5%	13.5%	6.0%	100%

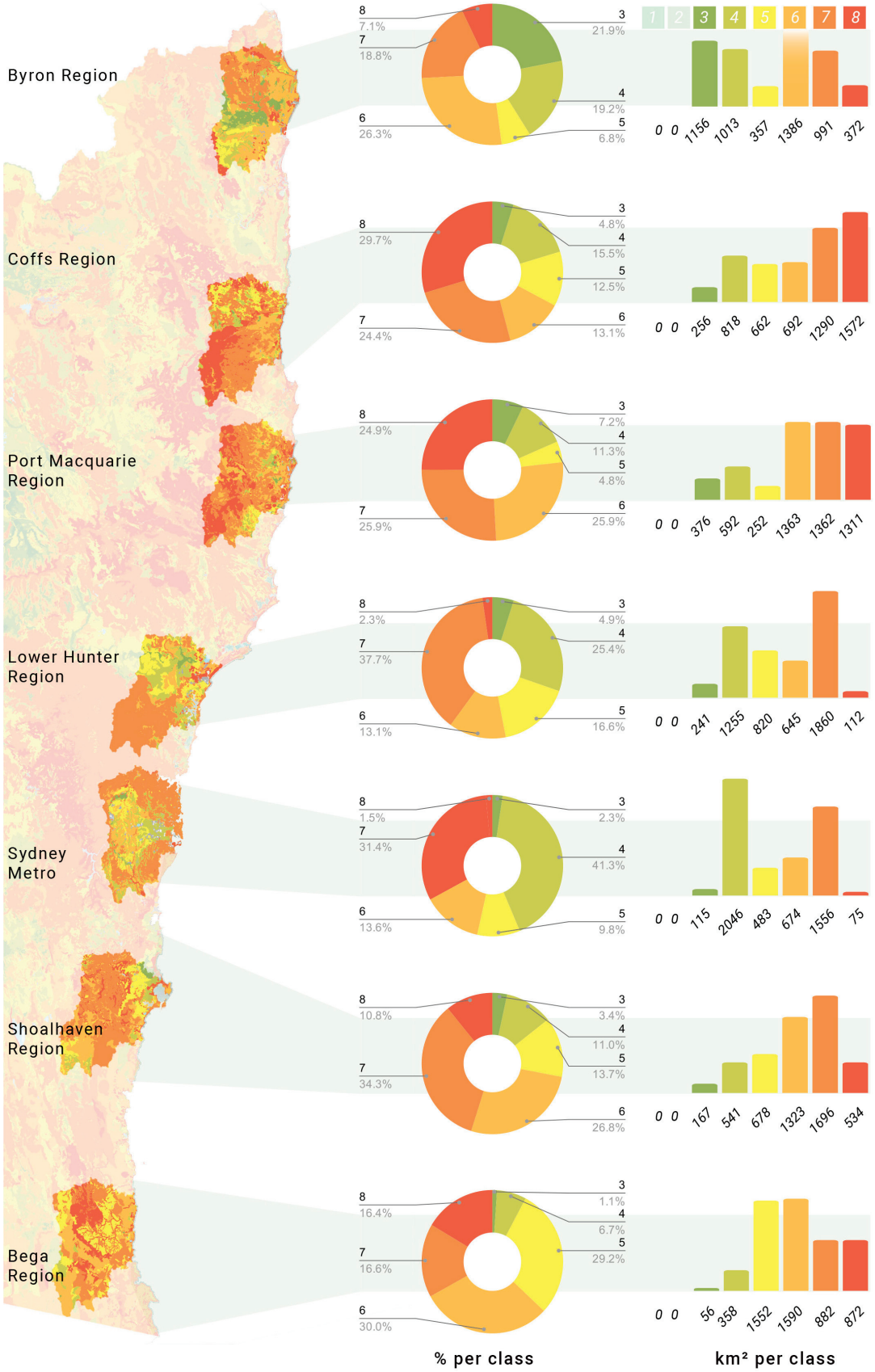


Figure 5. Land and Soil Capability (LSC) dataset comparisons for Method 1's boundaries, from class 1 (best) to 8 (worst). Figure by Josh Gowers and Joshua Zeunert. Data sources: NSW Government noted in Table 2.

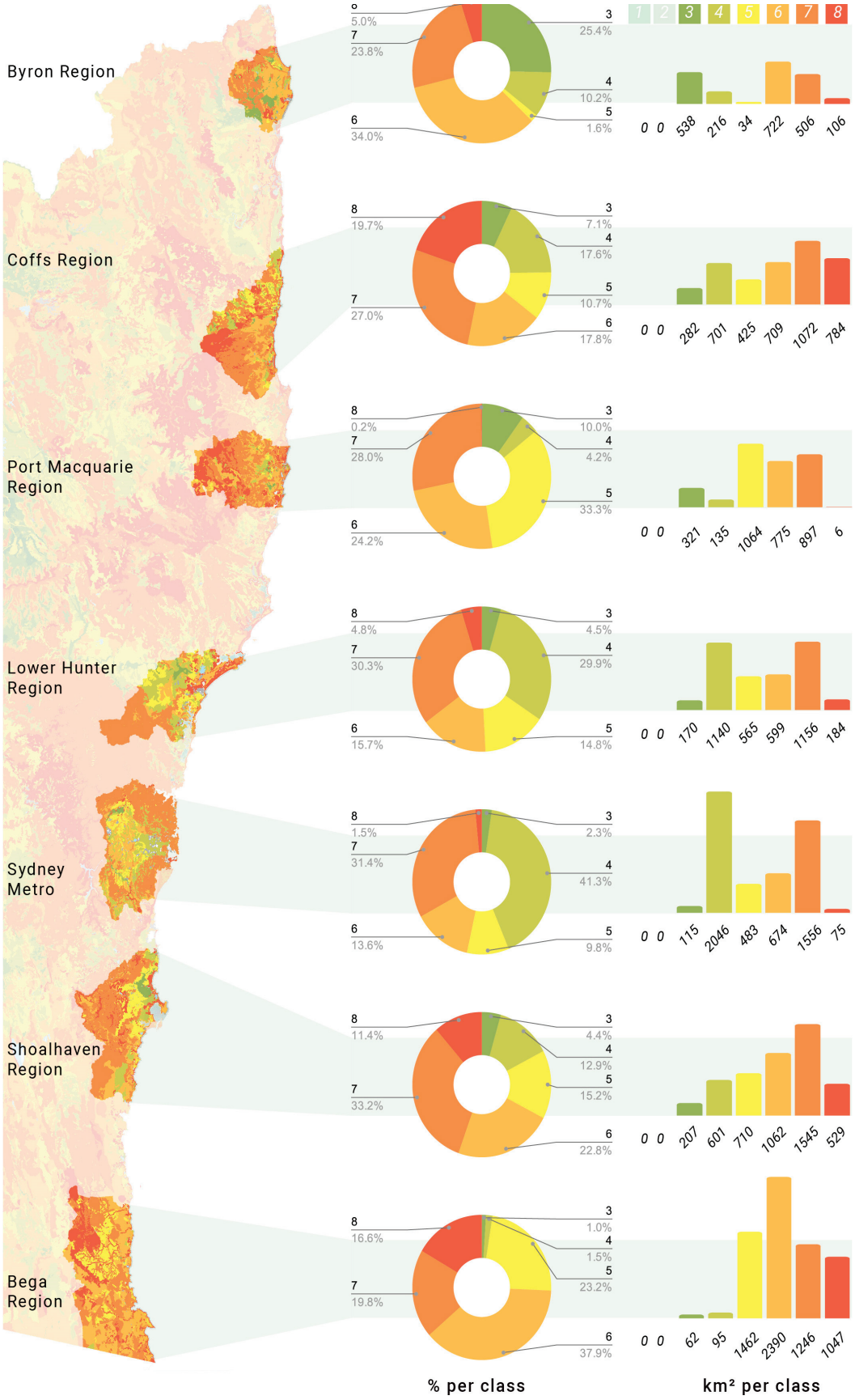


Figure 6. This Land and Soil Capability (LSC) dataset comparisons for Method 2's boundaries, from class 1 (best) to 8 (worst). Figure by Josh Gowers and Joshua Zeunert. Data sources: NSW Government noted in Table 2.

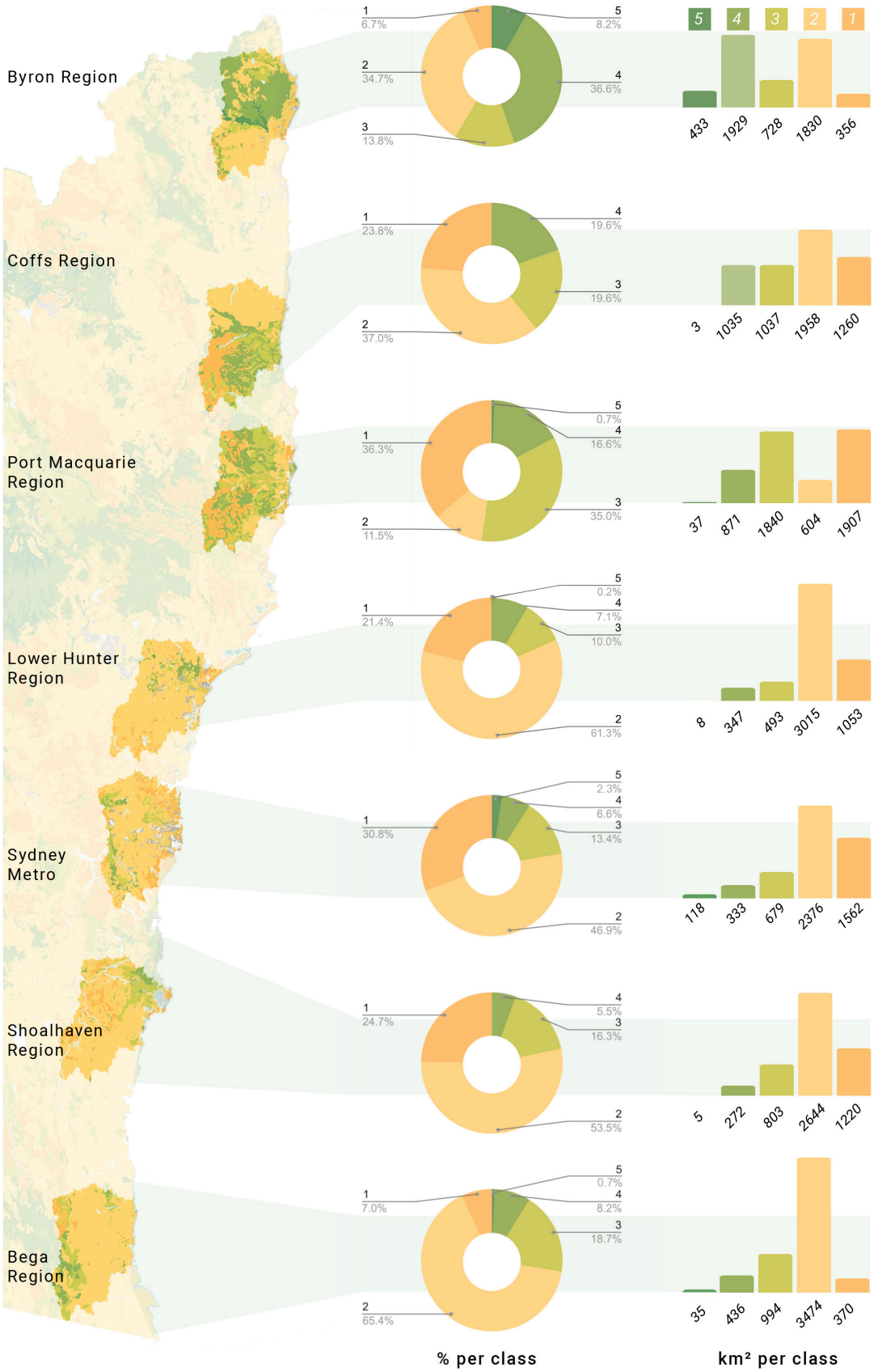


Figure 7. Inherent Soil Fertility (ISF) dataset comparisons for Method 1's boundaries, from Class 5 (best) to 1 (worst). Figure by Josh Gowers and Joshua Zeunert. Data sources: NSW Government noted in Table 2.

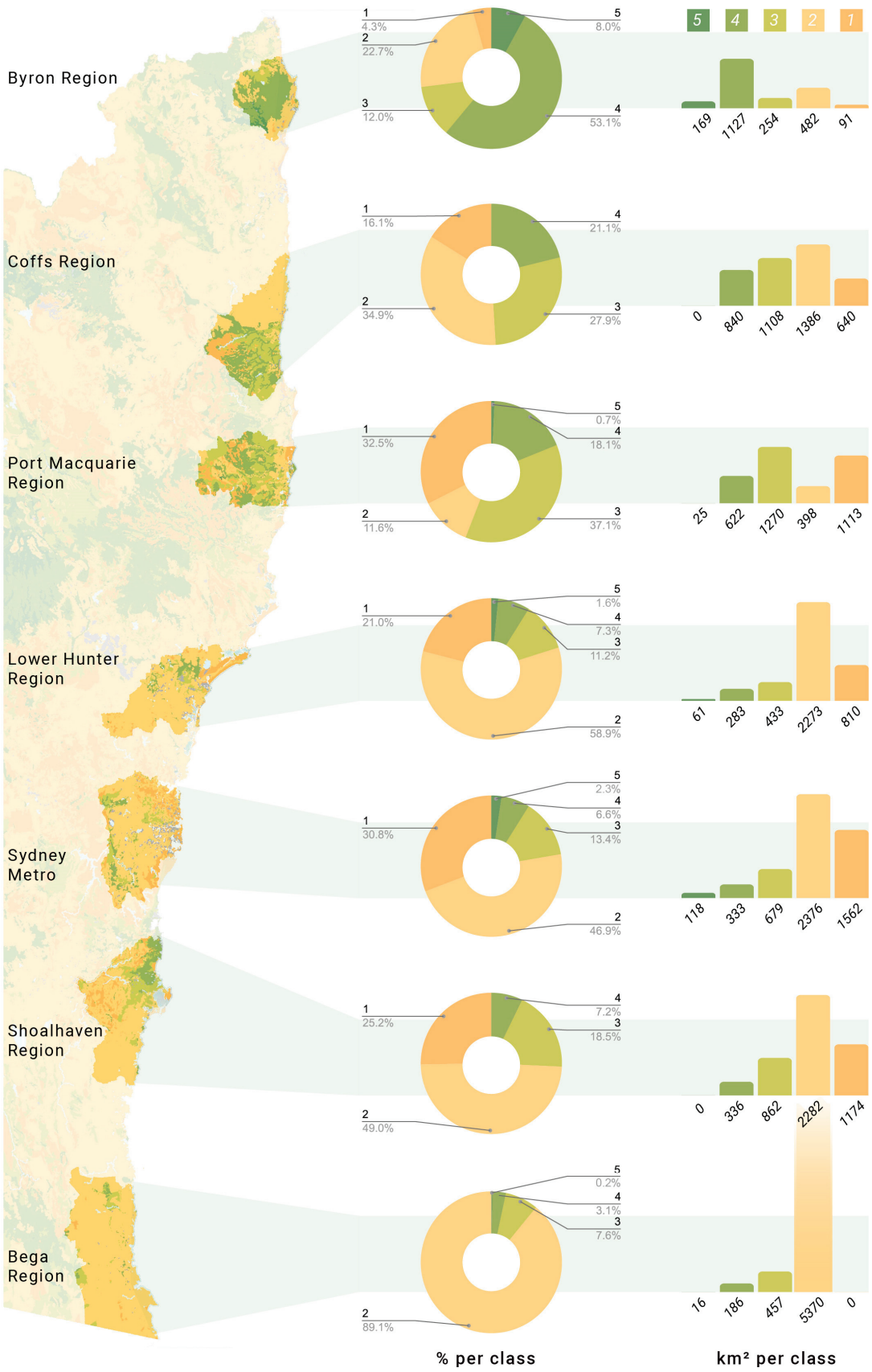


Figure 8. Inherent Soil Fertility (ISF) dataset comparisons for Method 2's boundaries, from Class 5 (best) to 1 (worst). Figure by Josh Gowers and Joshua Zeunert. Data sources: NSW Government noted in Table 2.

Table 4. This shows Land Soil and Capability results based on Method 2 boundary areas for each region (and NSW total). Each region shows three rows of data: land area for each class of land (1–8) in km^2; the percentage of each class within the total area of each region (km^2); and comparative rankings/7 for each region based on percentages. Class colours correlate across all LSC figures and tables.

Class/Case	(Best) 1	2	3	4	5	6	7	(Worst) 8	Total km^2
Byron (km^2)	0	0	538	216	34	722	506	106	2123
%	0%	0%	25.3%	10.2%	1.6%	34%	23.8%	5.0%	100%
Rank/7			1	5	7	2	5	6	
Coffs	0	0	282	701	425	709	1072	784	3974
%	0%	0%	7.1%	17.6%	10.7%	17.8%	27.0%	19.7%	100%
Rank/7			3	3	5	5	6	1	
P. Macq	0	0	321	135	1064	775	897	6	3198
%	0%	0%	10.0%	4.2%	33.3%	24.2%	28.0%	0.2%	100%
Rank/7			2	6	1	3	4	7	
L. Hunter	0	0	170	1140	565	599	1156	184	3814
%	0%	0%	4.5%	29.9%	14.8%	15.7%	30.3%	4.8%	100%
Rank/7			4	2	4	6	3	4	
Sydney	0	0	115	2046	483	674	1556	75	4949
%	0%	0%	2.3%	41.3%	9.8%	13.6%	31.4%	1.5%	100%
Rank/7			6	1	6	7	2	5	
Shoalhaven	0	0	207	601	710	1062	1545	529	4654
%	0%	0%	4.4%	12.9%	15.2%	22.8%	33.2%	11.4%	100%
Rank/7			5	4	3	4	1	3	
Bega	0	0	62	95	1462	2390	1246	1047	6302
%	0%	0%	1.0%	1.5%	23.2%	37.9%	19.8%	16.6%	100%
Rank/7			7	7	2	1	7	2	
NSW	0	14,659	116,025	190,846	154,928	174,023	108,783	48,889	808,153
%	0%	1.8%	14.4%	23.6%	19.2%	21.5%	13.5%	6.0%	100%

Table 5. Inherent Soil Fertility results based on Method 1 boundary areas for each region (and NSW total). Each region shows three rows of data: land area for each class of land (1–8) in km^2; the percentage of each class within the total area of each region (km^2); and comparative rankings/7 for each region based on percentages. Class colours correlate across all ISF figures and tables.

Class/Case	(Best) 5	4	3	2	(Worst) 1	Total km^2
Byron (km^2)	433	1929	728	1830	356	5275
%	8.2%	36.6%	13.8%	34.7%	6.7%	100%
Rank/7	1	1	5	6	7	
Coffs	0	1035	1037	1958	1260	5290
%	0%	19.6%	19.6%	37.0%	23.8%	100%
Rank/7	6	2	2	5	3	
P. Macq	37	871	1840	604	1907	5259
%	0.7%	16.6%	35.0%	11.5%	36.2%	100%
Rank/7	3	3	1	7	1	
L. Hunter	8	347	493	3015	1053	4917
%	0.2%	7.1%	10.0%	61.3%	21.4%	100%
Rank/7	5	5	7	2	5	
Sydney	118	333	679	2376	1562	5068
%	2.3%	6.6%	13.4%	46.9%	30.8%	100%
Rank/7	2	6	6	4	2	
Shoalhaven	0	272	803	2644	1220	4939
%	0%	5.5%	16.3%	53.5%	24.7%	100%
Rank/7	6	7	4	3	4	
Bega	35	436	994	3474	370	5310
%	0.7%	8.2%	18.7%	65.4%	7.0%	100%
Rank/7	4	4	3	1	6	
NSW	12,343	62,812	247,824	275,313	167,239	765,531
	1.6%	8.2%	32.4%	36.0%	21.8%	100%

Table 6. This shows Inherent Soil Fertility results based on Method 2 boundary areas for each region (and NSW total). Each region shows three rows of data: land area for each class of land (1–8) in km^2; the percentage of each class within the total area of each region (km^2); and comparative rankings/7 for each region based on percentages. Class colours correlate across all ISF figures and tables.

Class/Case	(Best) 5	4	3	2	(Worst) 1	Total km^2
Byron (km^2)	169	1127	254	482	91	2123
%	8.0%	53.1%	12.0%	22.7%	4.3%	100%
Rank/7	1	1	5	6	6	
Coffs	0	840	1108	1386	640	3974
%	0%	21.1%	27.9%	34.9%	16.1%	100%
Rank/7	6	2	2	5	5	
P. Macq	25	622	1270	398	1113	3428
%	0.7%	18.1%	37.1%	11.6%	32.5%	100%
Rank/7	4	3	1	7	1	
L. Hunter	61	283	433	2273	810	3859
%	1.6%	7.3%	11.2%	58.9%	21.0%	100%
Rank/7	3	4	6	2	4	
Sydney	118	333	679	2376	1562	5068
%	2.3%	6.6%	13.4%	46.9%	30.8%	100%
Rank/7	2	6	4	4	2	
Shoalhaven	0	336	862	2282	1174	4654
%	0%	7.2%	18.5%	49.0%	25.3%	100%
Rank/7	6	5	3	3	3	
Bega	16	186	457	5370	0	6029
%	0.3%	3.1%	7.6%	89.1%	0%	100%
Rank/7	5	7	7	1	7	
NSW	12,343	62,812	247,824	275,313	167,239	765,531
	1.6%	8.2%	32.4%	36.0%	21.8%	100%

Table 7. Biophysical Strategic Agricultural Land (BSAL) for Method's 1 (red) and 2 (blue).

BSAL	Method 1			Method 2		
	BSAL km^2	Boundary Area km^2	% of Area	BSAL km^2	Boundary Area km^2	% of Area
Byron	975	5293	18.4%	550	2346	23.5%
Coffs	245	5297	4.6%	279	4264	6.5%
Port Mac	294	5275	5.6%	176	3681	4.8%
LH	398	5012	7.9%	289	5794	5.0%
SYD	103	5340	1.9%	103	5340	1.9%
Nowra	163	4974	3.3%	201	4947	4.1%
Bega	35	5318	0.7%	47	6294	0.8%
NSW	30,945	810,213	3.8%			

Table 8. State Significant Agricultural Land (SSAL, draft dataset) for Method's 1 (red) and 2 (blue).

SSAL	Method 1			Method 2		
	SSAL km^2	Boundary Area km^2	% of Area	SSAL km^2	Boundary Area km^2	% of Area
Byron	2212	5293	41.8%	1091	2346	46.5
Coffs	414	5297	7.8%	419	4264	9.8
Port Mac	524	5275	9.9%	351	3681	9.5
LH	390	5012	7.8%	312	5794	5.4
SYD	246	5340	4.6%	246	5340	4.6
Nowra	199	4974	4.0%	242	4947	4.9
Bega	96	5318	1.8%	68	6294	1.1
NSW	94,914	810,213	11.7%			

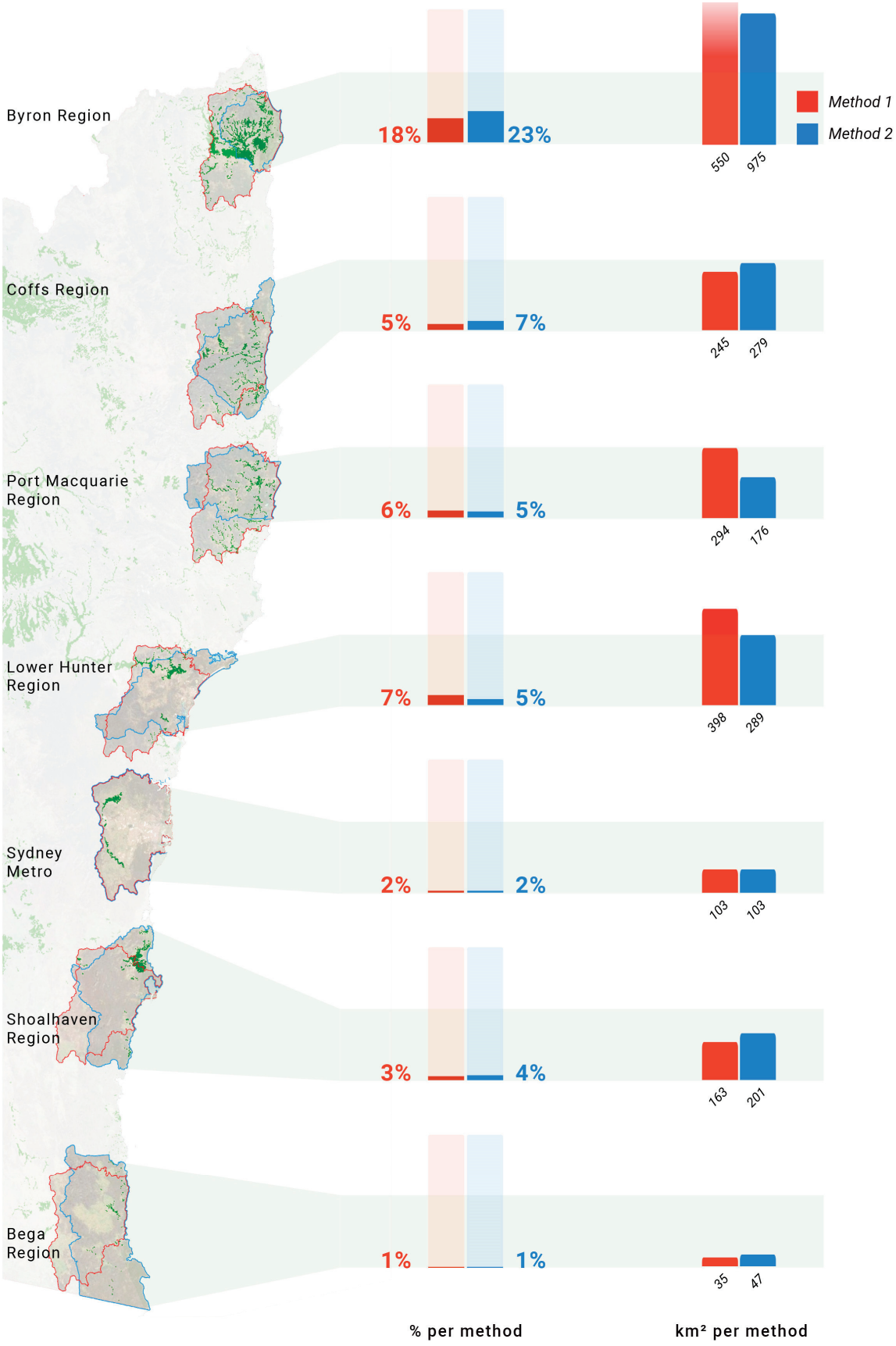


Figure 9. Biophysical Strategic Agricultural Land (BSAL) comparisons for both Methods, as percentages of total region area, and total km^2 for each region. Figure by Josh Gowers and Joshua Zeunert. Data sources: NSW Government noted in Table 2.

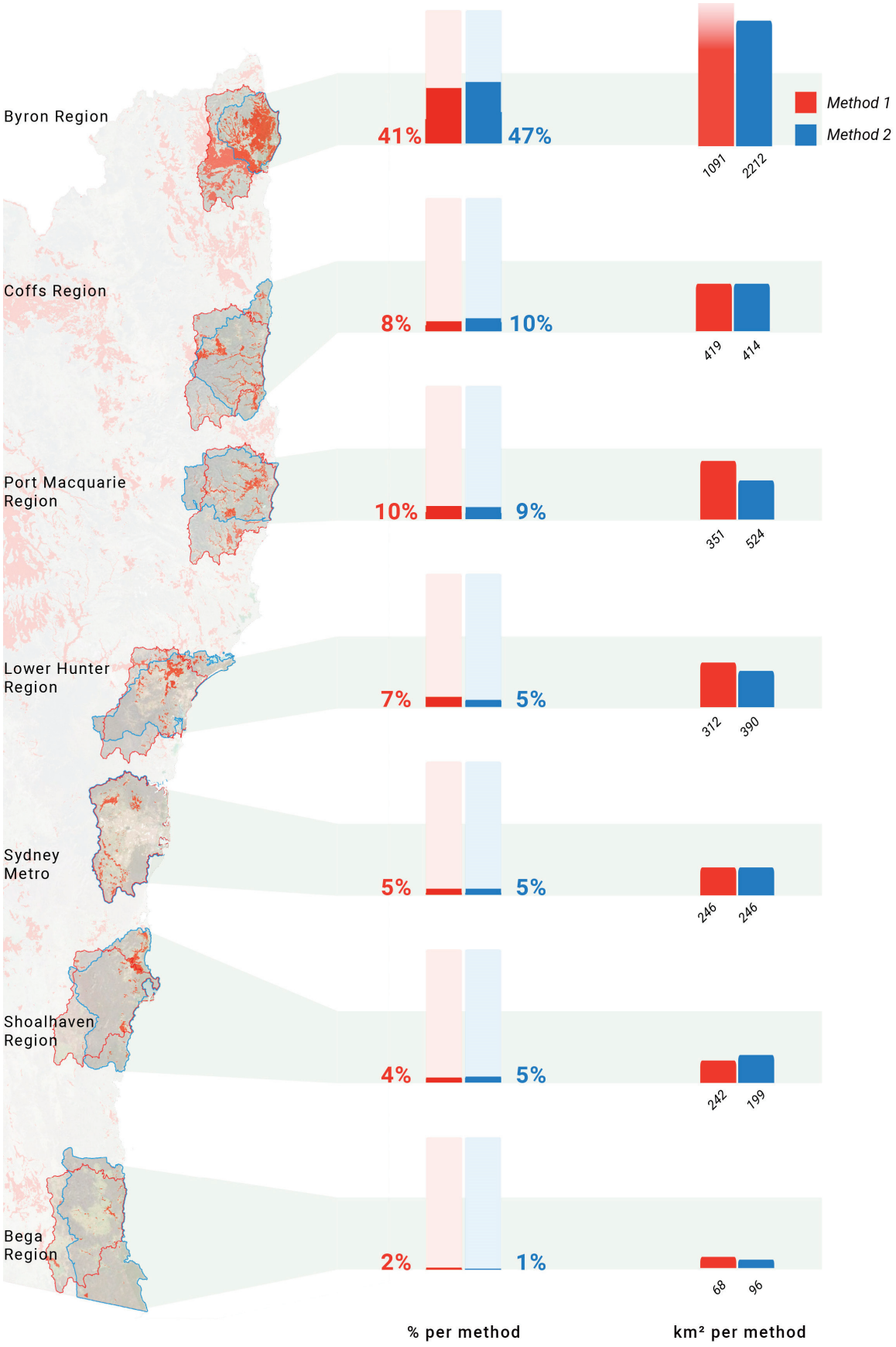


Figure 10. State Significant Agricultural Land (SSAL) comparisons for both Methods, as percentages of total region area, and total km^2 for each region. Figure by Josh Gowers and Joshua Zeunert. Data sources: NSW Government noted in Table 2.

The final analysis completed is shown in Figure 11, which shows the two highest classifications in LSC (Classes 3 and 4) and ISF (Class 5 and Class 4) and the proportions of these in each of the cases. Results are next discussed.

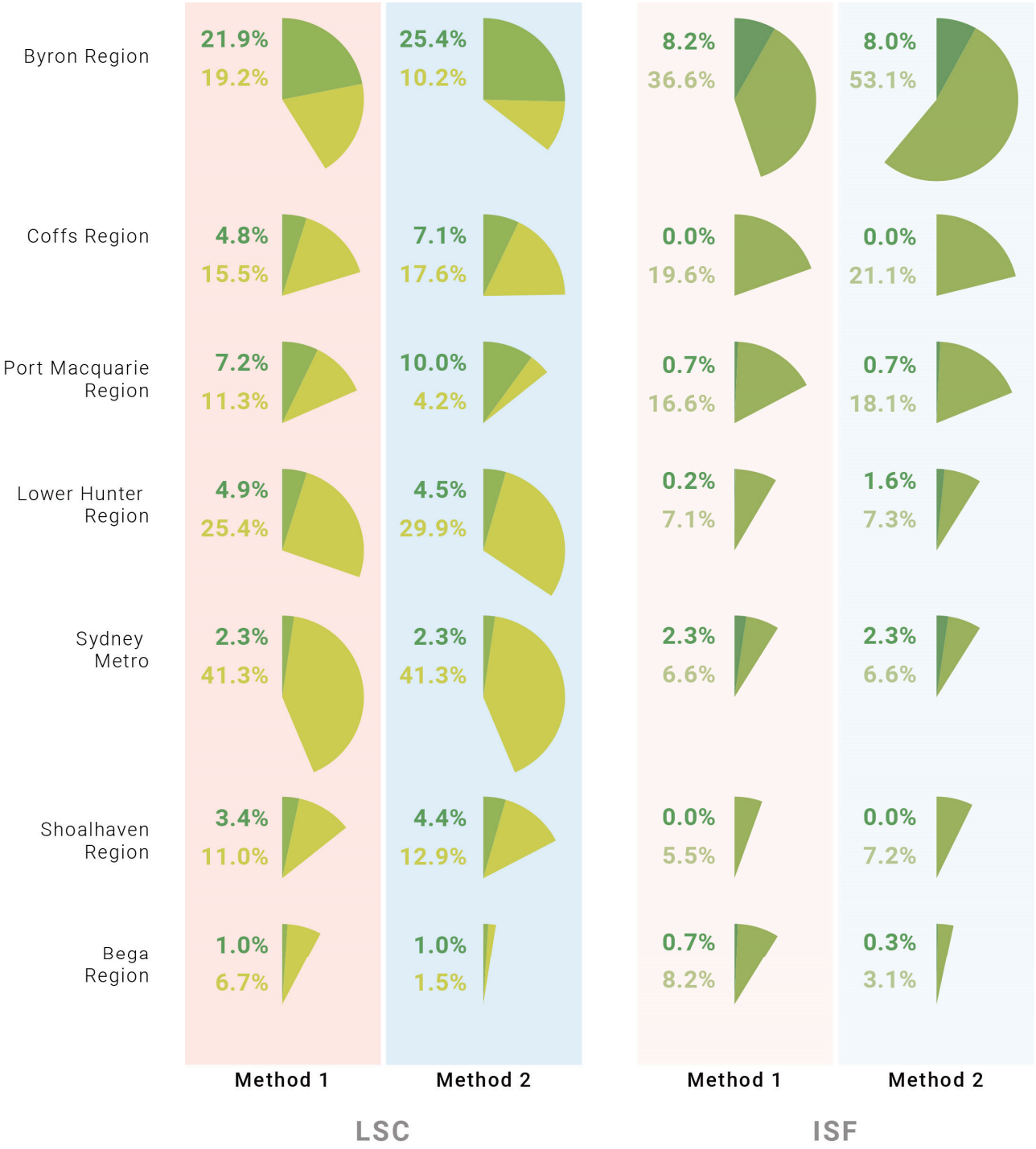


Figure 11. This figure shows the area proportion (%) of land in the study regions for the two highest ranked classifications in Land and Soil Capability (LSC) (Classes 3 and 4) and Inherent Soil Fertility (ISF) (Class 5 and Class 4), for both Methods. Refer to Table 2. Figure by Josh Gowers and Joshua Zeunert. Data sources: NSW Government noted in Table 2.

5. Discussion

By visualising all available datasets on agricultural capacity for urban regions along the NSW coast, various patterns are apparent. We next discuss our findings and structure these into four sections: key findings; policy and planning implications for Sydney; limitations; and finally, suggestions for further research.

5.1. Key Findings

Firstly, we can immediately see the finite and limited nature of quality agricultural land in each context, emphasising a need to appreciate the importance of conserving what is left, especially against the pressures of urban growth. In terms of inherent capacity for agriculture, Sydney possesses the highest land area of all seven cases of Class 4 LSC lands (2046 km^2 or 41.3% of total land area)—being the second highest-ranked LSC category east of NSW's Great Dividing Range. This inherent capacity is independent of whether this land is presently reflected in productive agricultural uses or not (see Sections 5.2 and 5.3). We aim to present the data so that remnant and unprotected metropolitan, peri-urban, and urban agricultural landscapes can form the basis of a new push to conserve, enhance, and expand agricultural capacity within Sydney and other urban coastal regions (see Section 5.2). Researchers such as McDougald [60] and others [51] suggest there is potential to expand food production within the city of Sydney to provide as much as 15% of the required food supply through adapting current marginalised urban spaces such as street verges. However, a much better approach is to conserve and support greater use of existing agricultural lands and their soils within the metropolitan region, as well as their social ecosystems [61] and economic structures shaping viability (see Section 6). Soils that have already been transformed through intense urban land uses are not easily converted back into agricultural lands due to potential contaminations, fragmentation of parcels, and unsuitable adjacent land uses [22].

Secondly, wider spatial-data contextualisation and comparison of Sydney with other NSW coastal regions reveals the city's agricultural capacity, based on all four viable government datasets. Sydney is broadly comparable with five comparison regions: Coffs, Port Macquarie, Lower Hunter; Shoalhaven, and Bega—and undoubtedly superior to the last two. Most of these regions possess agricultural identity: Coffs (subtropical fruits); Hunter (wine), and Bega (and to a lesser degree Shoalhaven) (dairy products). As an overall appraisal, therefore, the results may be surprising in quantifying Sydney as a comparatively capable agricultural region—and indeed, a deeper historical analysis of the city reveals this rich legacy [22,25]. Sydney has the largest total area of agriculturally capable land falling within the highest two Land and Soil Capability classifications (Classes 3 and 4), albeit only 2.5–8% more than the Byron region, which has considerably more higher-quality Class-3 lands (19.6–23.1%), and Byron is emphatically the superior region of all seven cases and all four datasets.

Our third finding is that Class 3 LSC, Class 5 ISF, BSAL, and SSAL lands need to be given much greater emphasis and protection against urban encroachment and development (see Section 5.2). Focusing on Class 3 LSC lands, these are classified as possessing few agricultural limitations in regards to water erosion, wind erosion, salinity, topsoil acidification, shallow soils/rockiness, soil structure decline, waterlogging, and mass movement. While Class 3 LSC lands constitute a small total proportion of the overall area of each case—Coffs 4.8–7.1%; 7.2–10% for Port Macquarie; Lower Hunter 4.9–4.5%; Shoalhaven 3.4–4.4%; Sydney 2.3%; and Bega 1%—they present precious opportunities for agricultural production in proximity to consumer bases. Despite this, areas of Class 3 lands in Sydney, such as in the Hawkesbury and Richmond regions, continue to be lost from agricultural land through rezonings for urban development [22]. This is especially concerning seeing

that these agricultural lands are frequently susceptible to flooding, which poses a significant risk for housing and other forms of habitation and urban development.

Our fourth finding is that both correlations and variations exist between the four datasets, which is consistent with their data statements [53]. For the ISF dataset, the Byron region unsurprisingly is the clear winner. Sydney does not fare as well in the ISF as the LSC. Other case regions have larger proportions of Class 4 (moderately high) ISF lands, with Sydney ranking fifth (Method 1) and sixth (Method 2). This is clearly evident in the expression of key results in Figure 11. Overall, however, we emphasise the importance of protecting lands in the two highest present classes from urban development—Classes 5 and 4 in ISF and Classes 3 and 4 in LSC.

Fifth, the Biophysical Strategic Agricultural Lands and State Significant Agricultural Lands (Figures 9 and 10 and Table 8) show the Byron region containing by far the best agricultural production lands of the seven cases, over three times any other case. BSAL and SSAL results for the other six cases are more comparable, ranging between 1 and 10% of the total area. Like the LSC and ISF, BSAL and SSAL lands are crucial for protection against urban development.

Our sixth finding is related to the lack of consideration of metropolitan and urban agriculture within policy and consultant reports at the state and national levels. Clarke's [19] dismissal of Sydney's agricultural capacity—largely based on the LSC dataset—can be attributed to a narrow focus on a single urban region and a set of financial values skewed by land speculation activities [22]. This analysis gave legitimacy for the Greater Sydney Commission to execute their concept of a third city for Sydney, the 'Western Parkland City' (WPC). Its 184,500 new dwellings, 81% as detached housing, continue to encroach on the Sydney region's remnant food production lands [22]. Much of the WPC area is beset by a range of urban growth and human-health habitability challenges including flood-prone lands, acid-sulphate soils, poor air quality, and a hot climate. The WPC is not currently well serviced by existing or planned transport networks, especially public transport [62,63], equating to heavy private vehicle dependence. This reflects NSW and Sydney urban planning agendas geared to transport- and embodied energy-intensive national and global food systems that eschew metropolitan-scale food production. Despite all the advantages of the area for agriculture and the disadvantages for urban habitation, the urban growth machine mentality excludes the consideration of more balanced development approaches that retain food production.

5.2. Implications for Metropolitan Sydney's Policy and Planning

Recent official planning efforts regarding Sydney's agricultural production capacity demonstrate selective data bias, particularly highlighted in the 2018 Sydney Metropolitan Strategy through Clarke et al.'s report [19]. This report utilised the identical LSC dataset used in our research. This key report [19] failed to adequately contextualise its findings, notably failing to mention the complete absence of Class 1 Land and Soil Capability (LSC) lands throughout NSW and the minimal 1.8% of the entire state classified as Class 2 (with 99.97% of this occurring west of the Great Diving Range and thus disconnected from the vast majority of the State's population base). When considered in this light, the relative value of the Classes 3 and 4 LSC lands visualised and presented in this paper are apparent. Consequently, for the vast majority of NSW and particularly in the eastern seaboard, where the majority of the population resides, Class 4 LSC areas emerge as significant agricultural production lands proximate to consumer bases.

Our analysis reveals that Sydney possesses a significant proportion of these Class 4 lands, accounting for 41.3% of the total area (2046 km^2), which is markedly higher than other regions such as Lower Hunter (25.4–29.9%), Coffs (15.5–17.6%), Byron (19.2–10.2%),

Shoalhaven (11–12.9%), Port Macquarie (11.3–4.2%), and Bega (6.7–1.5%). This indicates that if agriculture is regarded as a culturally valuable practice east of the Great Dividing Range in NSW, Sydney represents a significant region for agricultural production based on its inherent capacity.

The implications of such analyses and findings are critical for future land use planning and agricultural policy, as they emphasise the importance of recognising the agricultural potential of Sydney in the context of urban development and population density, which if planned carefully, can coexist through prudent medium and high-density development models to conserve agricultural landscapes. Our central planning recommendation would be to legislate protection of Class 3 LSC (115 km^2), Class 5 ISF (118 km^2), and Class 4 ISF (333 km^2), BSAL (103 km^2), and SSAL (246 km^2) lands within metropolitan Sydney (see Section 5.4 to ascertain their overlap), as well as existing market gardens and other spatially and nutritionally efficient food production lands. Prohibiting the rezoning of these significant agricultural lands can be supported through complementary policies such as establishing adequate buffer zones to protect them from encroachment and land use conflict. Protection for Sydney's Class 4 LSC lands (2046 km^2) would prove very challenging due to their significant spatial area, existing variety of current activities, and significant departure from the trajectory of over seventy years of official metropolitan planning [32] treating peri-urban agricultural land conversion as necessary in a city-growth agenda [22,32,61]. A more achievable strategy would be to identify existing operational farms and existing land zoned as agricultural within the Class 4 LSC land area, as suggested in this study's recommendations for further research below.

In the context of a rapidly growing metropolis, where land values are high, a key agricultural dynamic is the nexus of spatial efficiency, high-value products, high nutritional content, and minimised likelihood of conflicts with adjacent land uses. While poultry farming is by far Sydney's most economically valuable activity [19] due to industrial (and inhumane) production approaches being very spatially efficient [64], its rank odours routinely conflict with adjacent land uses, regularly several kilometres away [65]. Market gardening and mushroom farming are likely the two most synergistic urban agricultural activities achieving a balance of this nexus in the Sydney context [22]. Market gardening is particularly important for its high nutritional density in fresh vegetables, herbs, and leafy greens, crucially important if refrigerated long-distance supply chains are interrupted or compromised under future scenarios, further emphasising the city's topographically and aquatically challenging accessibility, with other significant agricultural production regions hundreds and thousands of kilometres away (Figure 2).

5.3. Limitations

Many factors affect agricultural production dynamics and consideration of the full range of relevant factors is outside the scope of this research. Our chief limitation, which is a direct result of the dataset particulars as noted in their user guide [66], is their orientation to broadscale and rural agricultural practices such as cropping and livestock grazing. The LSC dataset, for example, is noted as "less applicable for high intensity [agricultural] land use", being "suitable for broadscale assessment of land capability, particularly for assessment of lower intensity, dry-land agricultural land use" [66]. While our study's broadscale methodological analysis and scale intentionally aligns with this dataset characteristic, it is nonetheless geared to more theoretical inherent comparative production capacity rather than actual activities 'on the ground'.

No datasets exist geared toward intensive metropolitan and peri-urban agricultural approaches, which are particularly influenced by economic, social, and infrastructural factors due to close proximities to large consumer markets and workforces—which can

both increase and decrease the economic viability of certain lands and practices. While such complexities are understandably difficult to frame and articulate in a single dataset, we suggest such endeavours might be undertaken to factor in other types of metropolitan and urban values.

5.4. Further Research to Inform Policy and Planning

To inform and develop specific policy and planning recommendations for metropolitan Sydney, we suggest that research would be beneficial in the following three key areas. These encompass strategic planning focused on soils, systematic monitoring of agricultural land use change, and developing datasets that can better quantify the value of agriculture within cities.

Firstly, future research on strategic protection of agricultural soils in metropolitan Sydney and nearby urban regions might focus on better understanding current production in relation to development pressures. Whilst our research reviews inherent capacity, it does not address current operational food production areas nor systematically identify potential risks through future development. Further research could therefore quantify remaining agriculturally zoned lands and then develop strategic zoning of agricultural soil landscapes for current and future use. Such research can be informed through global best practices identifying relevant policies from around Australia and the world. Various mechanisms, including buffer zones between urban and agricultural uses, permanent agricultural reserves, transfer of development rights programmes, and agricultural enterprise zoning, might enhance the use of high-quality soil landscapes for agricultural purposes. By developing a more nuanced understanding of soil capability in relation to urban development pressures and patterns, planners can create targeted strategies that preserve the most productive agricultural lands while accommodating desired urban growth [67]. Carbon accounting and future climate-sensitive policies are essential to such approaches and are a key area for future research [68].

Secondly, systematic documentation of agricultural land conversion provides compelling evidence to support stronger protection policies. Using time-series aerial imagery and satellite data, researchers might establish comprehensive "before and after" comparisons that illustrate the pace and pattern of agricultural land loss in metropolitan Sydney. This documentation, building upon existing piecemeal efforts (as shown in Figure 12), might track conversion rates, identify priority protection areas, and evaluate the effectiveness of current protection policies. These visualisations and associated open datasets [69] can function as powerful communication tools for policymakers and the public, clearly indicating the extent of irreversible agricultural land loss and creating urgency for protective action before remaining productive soils are permanently lost to development [70–72].

Finally, research on the socio-economic value of urban agriculture can strengthen the case for agricultural land protection [73–75]. This research would ideally document direct economic contributions through market analysis of urban food production, including employment generation, business revenue, and supply chain impacts. Additional values communicating food security benefits, cultural heritage preservation, educational opportunities, community cohesion, and ecosystem and mental health impacts could also provide a much more comprehensive and compelling picture of urban agriculture's multifaceted value. By quantifying these larger societal benefits, researchers help policymakers justify stronger protection measures for urban agricultural lands beyond the short-term narrow scope of urban growth engine considerations.

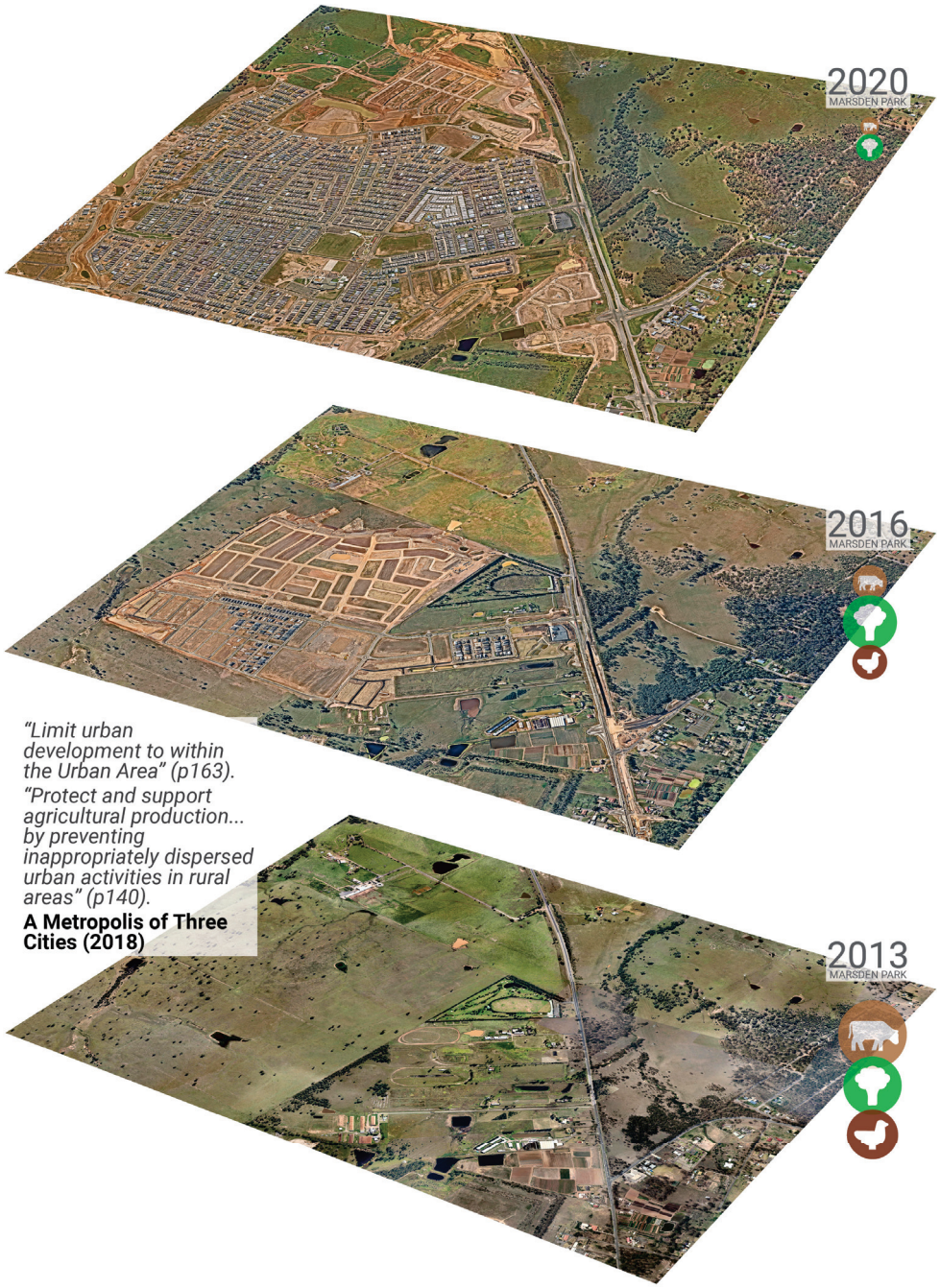


Figure 12. An example of using high-resolution aerial imagery to show land use change from agriculture to urban uses in Marsden Park, a peri-urban region of Sydney, contrasted with statements from the 2018 metropolitan strategy [27]. The agricultural symbols and their decline reflect changing land uses. Figure by Joshua Zeunert, adapted from Zeunert and Daroy [22].

6. Conclusions

The global loss of farmland to urban development highlights the need for balanced land use policies that promote sustainable urban development and preserve agricultural land to ensure food security for future generations. While this is true globally, it is particularly resonant in Sydney, where recent development has seen large agricultural areas rezoned to mixed-use centres, industrial estates, and residential development [25]. This transition has not been inevitable but manufactured through Sydney's growth machine coalition of developers, consultants, state planners, and resulting visions and policies. Through our analysis and discussion, we have developed an evidence-based counter-

narrative to this trajectory. Our findings, from critical GIS approaches, are contrary to the agricultural infertility narrative promulgated in expert and policy reports [19]: Sydney's land is biophysically capable of supporting agriculture, there is a significant amount of land that can do so, and this reflects a long legacy of the city [22].

In assessing metropolitan Sydney's biophysically inherent capacity for agricultural production, we demonstrated how datasets can either provide contextual insights or obscure understanding, as in the case of recent policy documents [19]. Such divergent outcomes are a vital consequence of the way spatial datasets shape city growth. We used the same dataset used to inform Sydney's most recent planning documents to draw markedly different conclusions for agriculture. While many factors beyond biophysically inherent capacity affect agricultural production dynamics—economic, social, and infrastructural [1]—the Clarke [19] report asserts that Sydney's agricultural lands are inherently low-value, marginal, and unworthy of protection. Our contextualised analysis of the LSC dataset across coastal NSW—the most respected and highest quality NSW Government dataset for biophysically inherent agricultural capacity—reveals this notion as false. This makes a crucial difference, informing decision-making for long-term metropolitan planning for Australia's largest city, as well as the agricultural interests of its inhabitants and their local food-supply security. Our research demonstrates the importance of utilising multiple datasets and case comparisons to contextualise spatial information to help avoid selective data bias and inappropriate conclusions [76].

In metropolitan contexts such as Sydney, short-term and narrowly focused economic policies have reduced agricultural capacity and urban sustainability [33,77]. We posit that broader economic values and analyses need to be used to assess metropolitan agriculture as a land use—as with biodiversity conservation, drinking water catchments, natural resources, infrastructures, heritage elements, scenic qualities, parks and recreation, sports, and other land uses. Metropolitan agriculture contributes cultural, environmental, social, and strategic values extending well beyond short-term economic measures.

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Perspective

Towards a De-Polarisation of Climate Guidance for Landscape Design and Policy

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Abstract: For disciplines and professions concerned with the design and management of the physical environment, climate emergency has become an integral part of research and practice because these environmental challenges are inextricably linked to the land and how we use it. Working from an understanding of landscape as the vast infrastructure upon which we depend for everything, landscape is the setting for all matters of environmental sustainability, impacting towns, cities, and countryside, communities and well-being, economics, governance, and politics. This paper explores the extent to which landscape and landscape design are considered in professional guidance pertaining to climate emergencies and environmental sustainability. Noting a tendency for such policy and guidance in the UK to cluster around the opposite poles of generalised targets and highly detailed technological solutions, this paper raises questions about what is missing from the middle of this spectrum. Our findings show that beyond carbon and biodiversity targets and the technological solutions to meet them, policy has been slow to respond to the climate emergency in relation to the landscape level. Furthermore, policy frameworks largely fail to account for the cultural and/or intangible factors affecting carbon and sustainability measures, such as the quality of space and well-being. This research suggests that guidance and policy relating to holistic, integrated understandings of landscapes are key to addressing the climate emergency, which also provides quality places and spaces for our communities and nature alike.

Keywords: climate emergency; design; environment; landscape; policy; sustainability; systemic change

1. Introduction

Dealing with the impact of professional guidance that addresses environmental challenges concerning the landscape, this paper acknowledges the need to revisit and review policy and governance focusing on the climate crisis [1] at both international and local levels. This paper examines the scale at which current environmental policy and guidance impact landscape strategy and design, from guidance that has no spatial implications, termed the 'rhetorical/conceptual scale' (e.g., a target to reduce carbon emissions), to a detailed/technology scale (e.g., design guidance on the construction of permeable paving to alleviate urban flooding). This paper aims to articulate the existence of a gap in policy and guidance that connects environmental challenges to strategy and design at a 'landscape scale' (i.e., with spatial implications at scales spanning national, regional, and local, but above that of construction detail—see Figure 1). We call on the academic community to urgently address this gap.

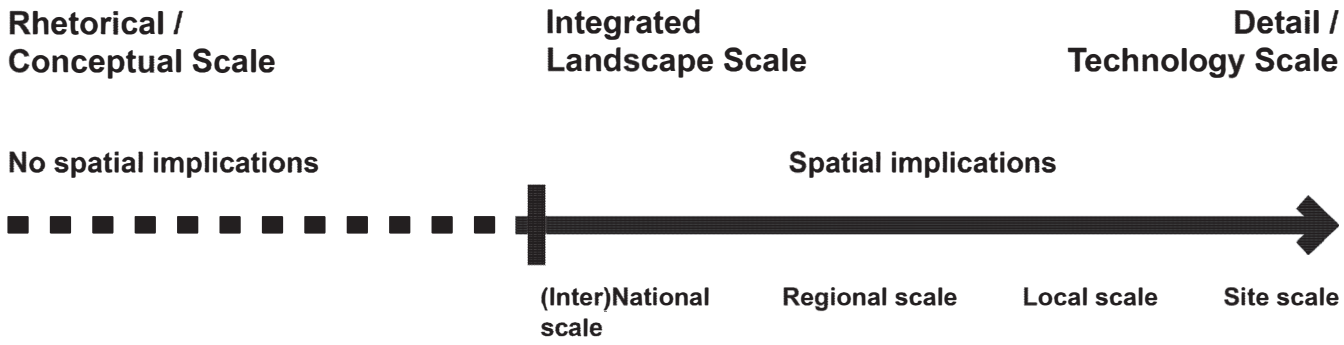


Figure 1. Representation of the scales at which policy and guidance connect environmental challenges to design and strategy.

This study explores selected professional guidance relating to landscape, landscape design, climate, and sustainability, aiming to define the importance of guidance that deals with aspects of landscape over and above physical matters pertaining only to 'the land'. Building on Kathryn Moore's positioning of landscape as 'the relationship between people and their territory; the physical, cultural context of our lives, the vast infrastructure upon which we depend for everything' [2–4], this paper integrates a broader definition of landscape. The authors, and a majority of landscape professionals, understand landscape to be both physical and relational: the result of natural forces and human action and the manifestation of society's relationship with the environment. This relationship can be healthy and nurturing, though it can also be destructive and exploitative.

Ramos et al. state that even though landscape is an important asset for our well-being, communities and quality of life, there is fragmentation in its interaction in policy and science [5]. Zhou et al. [6] identify that current discourse relating to landscape sustainability and sustainable landscapes tends towards matters of landscape ecology, ecosystem services and landscape planning, bypassing the social and cultural factors associated with the landscape. Taking a broader approach, Stremke et al. [7] assert that the landscape has many 'powers' interrelated with human interactions and affects the quality of life. Most importantly, they suggest that landscapes have the power to 'resolve urgent questions many of us face' [7]. Despite this potential, there is a lack of guidance and policy articulating the value of landscapes and their potential to address the environmental challenges faced by our cities and regions. The identity of a place is sometimes used to evaluate the apparently intangible aspects of a landscape as it pertains to the quality of life [5]. However, this is not well integrated into current climate and sustainability guidance, and very few frameworks address such matters.

Despite the paucity of existing guidance, several international institutions recognise the need to reform policy [8], compounded by the added need to embed this within a holistic territorial approach that addresses the climate emergency [1]. As the professional body representing all UK landscape practitioners—from landscape scientists to urban designers—the Landscape Institute (LI) bucks this trend, publishing policy-related outputs either in the form of guidance to professionals or as a response to governmental policy. Documents such as the 'Climate and Biodiversity Action Plan' [9], the 'Carbon and Landscapes Technical Information Note' [10], and the 'Landscape and Carbon Report' [11] published by the LI aim to advocate for the importance of such concepts within relevant policy agendas. It is acknowledged that such outputs are designed for a relatively small professional community and that the real need is for such ideas to be discussed and developed at a political level, resulting in an actionable political framework that responds to environmental challenges from a landscape-led perspective. It is important to highlight that spatial developments and strategic landscape projects need to be driven by a broader

vision that incorporates principles and values related to climate emergency, environmental design, culture, and community. In cases where such concepts are supported by local or national policies, the outcomes are of much better quality.

2. Literature Review

Much has changed since Peter Hall stated that 'planning decisions result from complex interactions among three groups of actors: the community, the bureaucrats and professionals within government; and the politicians at every level of government' [12], p. 47. While the equation still holds true, the context within which it operates has shifted. The climate crisis and environmental instability affect how these actors interact, especially in landscape design and planning, which are affected by the physical, social, cultural, and economic impacts of these global issues.

2.1. Development of Landscape Policy

The European Landscape Convention (ELC) explains that each country ratifying the convention should 'recognise landscapes in law as an essential component of people's surroundings, an expression of the diversity of their shared cultural and natural heritage, and a foundation of their identity [13]. Echoes of Hall's approach continue, as evidenced by the European Environment Agency encouraging the integration of policy, legislation, and politics in spatial strategies in areas such as urban sprawl, biodiversity loss, and soil sealing affecting agricultural land' [14], p. 330. In each instance, the importance of integration is highlighted, whether it be between landscape (natural and cultural), policy (via planning governance), or spatial design (to manage a shifting environmental crisis). We adopt the language of a 'landscape approach' for this integrated outlook, which builds on the foundations established by Moore's [4] reading of the landscape.

Mata Olmo and De Meer [15] assert that an action plan integrating a landscape approach and local administration policies and processes would be beneficial, especially if this involves 'cooperation and coordination between social, public and private agents, with feasible and sustainable economic alternatives, capable of strengthening the landscape's social tissue'. Childress et al. [1] state that a landscape approach can address natural and biological systems 'within the confines of human-generated political or administrative boundaries', which is helpful in addressing localised responsibilities but overlooks alternative landscape scales that do not conform to human-centric boundaries such as river catchments, or climate zones. Although claiming to be a 'landscape approach, ' the model described by [1] calls for 'the demarcation, delineation, and depiction of land parcels over landscapes, 'which contrasts with an integrated landscape-scale approach. Alonso MCA et al. [16], have identified three areas that limit how landscape is understood at a governmental level: The division of disciplines and sectors and a lack of multidisciplinarity; A blindness to 'everyday' landscapes such as the urban landscape, which creates a 'disconnect between policy and practice'; and a 'gap between high-level political commitments and specific on-site decisions or solution' [16].

The relationship between science and policy in a landscape context was examined by Dramstad and Fjellstad [14], who questioned whether policies impact landscape strategies and sustainable development, concluding that a dialogue between science and policy is required to generate sustainable landscapes. Despite their 2011 call, the gap between the climate crisis and landscape policy still remains. Notwithstanding the encouraging landscape-led or landscape-scale rhetoric from politicians and organisations, this is rarely translated into policies dealing with land and development from an integrated understanding of the landscape and climate emergency [15]. Confirming MCA et al'.s [16] observation that policy and guidance relating to climate change tend to polarise between generalised

(often national) targets and detailed (often generic) technological solutions, the UK Government's Climate Change Act 2008 has the large-scale target to 'ensure that the net UK carbon account for the year 2050 is at least [100%] lower than the 1990 baseline' [17]. Focusing on greenhouse gas emissions, strategies to achieve this national target are delegated to government departments, each of which proposes plans to contribute to the national picture according to their remit. The Department for Energy Security and Net Zero's Clean Power 2030 Action Plan, for example, proposes 'cleaning up our power system' as 'central to decarbonising the whole economy' [18] by growing renewable industries, attracting investment, and deploying clean technologies at scale. This national-scale strategy only mentions landscapes in passing, relating to the siting of overhead power lines in nationally designated landscapes, highlighting the need to look at the documentation of organisations further down the chain, with responsibility for implementing government-level strategies.

The landscape is frequently perceived merely as the location where development evolves, without acknowledging its importance from a cultural and social standpoint and how it is shaped by matters of politics and identity. Ramos et al. [5] assert that policy can support landscape identity, creating a happier and more satisfied, bonded community and establishing the idea of the landscape ('their' landscape) with local actors and stakeholders. Rose acknowledges that power, politics, and legislation play a major role in how the landscape is perceived, arguing that 'the politics of landscape traditionally refer to the political content of landscape representation' [19]. The Council of Europe has a similar approach, explaining that a framework based on policy and legislation for the landscape can be beneficial for the way the public and communities understand their surroundings, resulting in a greater impact of policy implementation [13]. From a landscape perspective, resilience and sustainability should always include matters of spatial planning, environment, culture, transport, economics, agriculture, engineering, health, education, and more. Healey uses the term 'strategic' to describe a higher level of administration or a broader scale of policy. She argues that planning 'implies a mode of governance (a form of politics) driven by the articulation of policies through some kind of deliberative process and the judgement of collective action in relation to these policies' [20]. Moreover, strategic spatial planning can be an advocate for municipalities or regional administrations, implying that it has a significant political role to play [21,22].

There is little evidence from the literature of landscapes being integrated into either regional and town planning policies or cultural, social, environmental, economic, and agricultural policies [23]. In addition, little evidence was found to demonstrate that policies relating to climate include the landscape as a distinct factor or integrate climate, landscape, and policy in any meaningful way. Often, policies that deal with landscape planning identify the ways in which the land is expected to change [24], but it is not clear if these changes relate to environmental and climate aspects or are limited to matters of planning, such as population growth and infrastructure provision. Ramos et al. [5] suggest that designers and spatial planners have a responsibility to create sustainable visions and, therefore, contribute to the wider well-being and quality of life of the community.

2.2. Climate Emergencies and Landscape Policy

Sanjuan [25] asks, 'Why are landscape visions so important? And how could these be interpreted into policy?' Describing the climate crisis as a 'high-stakes, high-profile and highly politicised issue [26], it is now clearer than ever that it has a landscape, cultural, economic, and political effect, even if the environmental challenges were initially seen in isolation. Alcoforado et al. [27] highlight instances where policy created to address the climate crisis did not manage to 'translate knowledge of the climate into guidelines for landscape design and planning', effectively derailing attempts to translate policy into

practice. Although much has shifted since Giannakourou [28] stated that the engagement of the 'European Union (EU) in spatial planning has no binding force and cannot prescribe concrete legal or institutional requirements' and EU policy and legislation incorporate environmental targets across multiple agendas, the landscape is still not considered in an integrated way in relation to the climate crisis. In contrast, South Korea's National Comprehensive Plan for Climate Change Adaptation was used as the basis for new policies created by the central and local governments [29]. This national plan provided inspiration for climate-related policies regarding architecture, urban planning, landscape architecture, and construction, as well as air and water quality, waste management, and natural resources [29]. Despite this apparent integration, the focus of policies related to landscapes is often confined to energy consumption. To fully understand and incorporate landscape sustainability into policy, we need to embrace all its biological, physical, and cultural characteristics interacting with the region and its communities [26]. As Alcoforado et al. [27] explain, planning procedures need to incorporate climatic guidelines but must also embrace social and economic elements, bearing in mind their importance to the identity, health, and well-being of citizens [27]. As a means of communicating the links between landscape, climate emergency, and policy, Sanjuan [25] discusses the importance of producing maps and atlases to illustrate how each impacts the other. This realm has received little attention and requires further research.

Overall, there is a scarcity of literature that connects climate, sustainability, and landscape to policy and guidance. A decade ago, Bridge et al. [30] described the low-carbon energy transition as a transformation of the landscape. With the focus then being on energy policy, the landscape was seen to play a key role [31,32] but was often perceived merely as the location of these energy technologies. In some cases, spatial planning policies were brought to the forefront, but mostly to allow ways in which the renewable energy transition could be implemented [33]. Such attitudes towards landscapes reinforce them as a 'canvas' upon which sustainable actions take place rather than the 'infrastructure upon which we rely' [4]. To this end, landscape policy and guidance must incorporate an integrated understanding of the natural, social, and cultural elements of a territory. Stremke et al. [7], put the new generation of landscape architects into the spotlight, explaining that the task of professionals is to embrace local value and accommodate the cultural landscapes of the 21st century. This approach is based on a recent study in the UK that revealed that in relation to renewable energy technologies, communities' main concerns were the impact on the landscape character of the area, the scale of a project, and the consequences for wildlife and habitats [34].

Similar issues are faced when dealing with the intangible concepts of a sense of place and spatial quality with design for low/net zero carbon. The interaction between the concepts of spatial quality and low carbon is not fully understood, creating issues with their integration into policy and legislation. Franssen is correct in stating that 'on [a] national level, the environment is [the] point of focus in-laws, which are of influence on spatial quality. However, at a national level, spatial quality is not literally discussed' [35]. De Jonge [36] also emphasises the difficulty in discussing ideas of spatial quality at a governmental level, and highlights a need to incorporate such expertise across governmental departments. Once a beacon of good practice, the Netherlands were more advanced in relation to carbon, environmental, and spatial quality arguments compared to the rest of Europe Franssen [35], but changes in the Dutch regional and national policy structure have weakened the integrated framework of spatial planning and the landscape. Discussing an integrated landscape approach, Moore states that in order 'to have any real chance of providing a sustainable and lasting blueprint for the landscape, this [new] way of working, needs to become wholeheartedly absorbed into all of the decision-making institutions

and organisations responsible for policy, strategic or regional planning at a national or international level' [2], p. 110, and [3].

In addition to the literature reviewed here, three further documents are considered below in more detail as illustrative examples of how climate change and sustainability are interpreted within policies and guidance for landscapes and landscape design.

3. Methodology

The aim of this positional paper is to raise awareness of the shortcomings of relating climate and sustainability policy/guidance to the landscape and landscape design through the evaluation of a small sample of pioneering cases. This sets the scene for further studies to undertake a comprehensive survey of policy/guidance to demonstrate the extent of the issues raised here. Each case study was analysed individually against the key themes identified below to ascertain the extent to which they addressed each theme and the implications thereof. They were then compared to identify similarities and differences, as well as best practices.

Key themes (articulated as assessment questions)
LINKS

- Does the policy/guidance link climate, sustainability, landscape, and landscape design?
    - To what extent/scale?

LANDSCAPE

- Does the policy/guidance have landscape implications
    - To what extent/at what scale?

DESIGN

- Does the policy/guidance have any design implications?
    - To what extent/at what scale?

Noting the tendency for UK climate and sustainability policy and guidance to cluster around the opposite poles of rhetorical targets and detailed technological solutions, this paper raises questions about what, if anything, is missing from the middle of this spectrum. We selected three policy/guidance approaches from the UK to demonstrate how landscape and landscape design are considered in the context of climate and sustainability policy/guidance and examined two European case studies to explore how the void at the centre of this polarised spectrum can be overcome.

Figure 2 illustrates this spectrum graphically. The left pole represents rhetorical, overarching, or general guidelines or policies such as 'reduce carbon emissions by 25%', or 'increase biodiversity'. The opposite end of the spectrum represents detailed, often technological solutions such as 'constructing swales' or 'using permeable paving'. The ccentre of the spectrum represents the translation and integration of overarching aims at a landscape scale, which is often absent—a conceptual void. A well-developed built landscape project must cover all aspects of the spectrum. Each case study is represented by blocks whose size and position on the scale are equivalent to its climate guidance in landscape design and policy. Multiple/split blocks represent guidance that jumps from high-level rhetoric to site scale detail with little or no intervening landscape-scale guidance.

Evidence for the UK examples is taken from published policy/guidance of national and local institutions: a national partnership (Natural England and the RSPB), a national professional institution (The Landscape Institute), and a local authority (Birmingham City Council). These institutions' policies/guidance were selected based on the authors' professional experiences with their impact and applicability to the industry. The documents were summarised and evaluated to ascertain the extent to which organisations with a vested

interest in the landscape publish policy and/or guidance that makes vital links between climate, sustainability, and landscape.

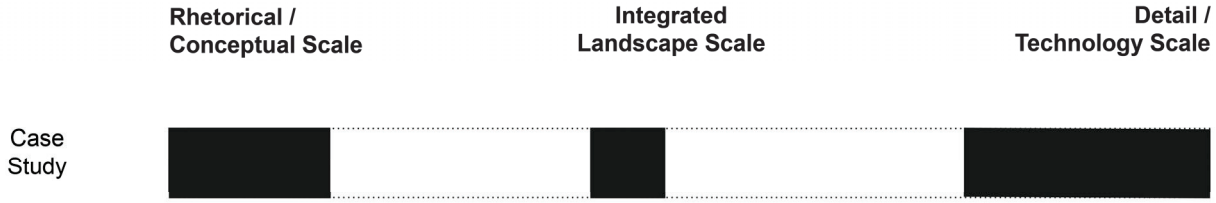


Figure 2. Representation of the extent to which case studies climate emergency and environmental sustainability at scale, from conceptl to detail.

Natural England is an executive non-departmental public body (established in 2006 by an Act of Parliament) sponsored by the Department for Environment, Food & Rural Affairs in England. It is the government's adviser on the natural environment in England, helping to protect and restore the natural world. The purpose of this body is to support sustainable development by helping to conserve, enhance, and manage the natural environment for the benefit of present and future generations. The priorities of Natural England align with the national strategy of the UK Government's 25-Year Environment Plan and aim to contribute to the challenge of climate change, society's well-being, community engagement, and nature's recovery. In this paper, we examine the Climate Change Adaptation Manual (NE751) published in 2020 in association with the RSPB (a UK environmental charity), focusing on Part 4 Green Infrastructure and Climate Change.

The Landscape Institute (UK) is the professional body of landscape architects representing the profession in the UK and advocating for landscapes and the wider environment. It also plays a role in responding to new government policies and legislation from this position. This professional body has established committees and processes to draft and assess connected aspects of environmental challenges, landscapes, and associated policies and guidance. In response, the LI publishes a range of action plans, policy guides, case studies, and reports. For this paper, we selected the Landscape for 2030 Case Study Report [37], which links climate evidence, policy, and landscape professions.

Birmingham City Council oversees the most populous local council area in the UK, with over one million inhabitants across 69 wards. The Council's City of Nature Plan is a programme that connects local, regional, and national policies and strategies aimed at creating a 'city of nature' with equal access to all communities, where sustainability plays a key role in open space management. The programme focuses on tackling environmental justice and accessibility to open space and introduces the UN SDGs as key metrics of the action plan to align this vision with specific indicators, including health, biodiversity, climate change, and social engagement. The programme concludes that its core aims and ethos should be accounted for at every stage of decision-making across each and every Council directorate, not only those traditionally associated with parks and open spaces [38].

To provide a context for comparison, two examples of best practices with proven landscape frameworks were selected from mainland Europe. The European Landscape Observatory (Catalonia) and Room for the River (Netherlands) were examined to track their progression and impact over time, as well as their influence on the political agenda. The Catalonia project focuses on landscape and social engagement, and the Netherlands project tackles climate change and landscape.

4. Results

4.1. Natural England and the RSPB—Climate Change Adaptation Manual (CCAM)

The Climate Change Adaptation Manual (Natural England, 2020) addresses the need to adopt a sustainable and cross-sectoral approach to adapting to a changing climate. Focusing on adaptation to the natural environment, the document nevertheless acknowledges the integration of natural and cultural aspects of the landscape and identifies that resilience should be addressed at varying spatial scales. While the report encourages 'landscape scale' approaches, the term is used rhetorically to describe largely undefined links between natural resources within an ecological network and management framework. With a focus on individual sites (nature reserves or Sites of Special Scientific Interest, for example) and natural assets, this report falls towards the 'detailed' end of the UK's clustering of guidance approaches. The remit of Natural England, including its Landscape Scale Change Assessment Methodology [39], is such that the range of assets it considers as part of the landscape is limited to 'natural features': habitat, species, geology, soils, historic remains, and ecosystem services [39]. This is a different way of understanding landscape compared to the integrated understanding set out at the beginning of this paper, and while no less valid, it reveals segregation and compartmentalisation of the landscape into component parts at a national level.

Turning to the specific guidance relating to green infrastructure and climate change, we expect to see implications for urban landscapes and their design. Accordingly, the report offers guidance on the delivery of green infrastructure to provide habitats for wildlife and improve the quality of life for communities while adapting to climate change. At face value, this appears to be an example of an integrated landscape approach; however, the focus is on managing and adapting to the effects of climate change on specific factors (temperature, water, soils, biodiversity, etc.) through very detailed interventions (swales, permeable pavements, soakaways, tree planting, etc.). While these intervention techniques have design implications, they are at the small-scale, site-specific 'detail' end of the spectrum, and the guidance does not consider design or spatial strategy at a landscape scale. The CCAM's advice on design is vague, stating that "good design is crucial" (Natural England, 2020 [39]), without explaining what good design looks like beyond the need for 'open space' and 'ecosystem services' (ibid). This is not to dismiss the benefits of open space or the enhancement of ecosystems; however, there is a noticeable lack of guidance on spatial strategy beyond the identification of a need to plan at different scales, illustrated within a flow diagram [39]. This guidance is represented by a series of segmented blocks: two separate blocks at the far ends of the spectrum representing polarised guidance and a series of small, separate blocks in the centre to represent compartmentalised landscape-scale thinking (Figure 3).

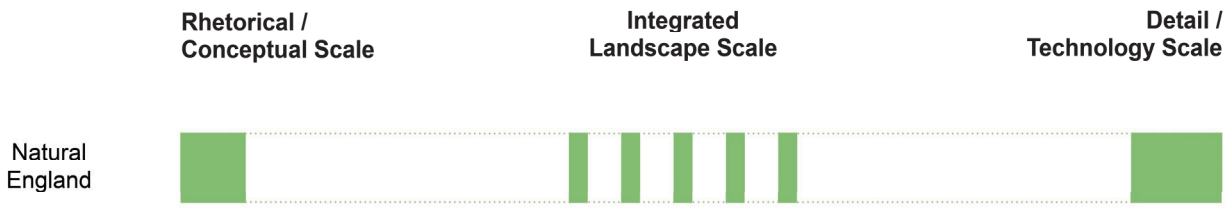


Figure 3. Natural England and RSPB, CCAM spectrum evaluation.

4.2. Landscape Institute—Landscape for 2030 Case Study Report (2021)

This report is, in part, a response to the UK Government Climate Change Committee's 2017 call for "professional bodies . . . to increase their level of engagement with members regarding climate change and to improve the training, guidance and professional accreditation they offer" [37]. As an example of how the Government's high-level (generalised)

targets are actioned through delegated processes, this report provides examples of how practitioners have, through design and technology, addressed specific risks of flooding and drought, temperature rises, threats to natural capital, biodiversity, and food supply. The implications for the landscape are clearly articulated, which is to be expected given the remit of the LI; nevertheless the report's focus is on describing the technologies employed to address the various problems identified. Given the brevity of the report, matters of design, aesthetics, and spatial strategy are not widely discussed, presenting an area for further research and expansion of the case studies included therein.

It is encouraging that the report acknowledges that the landscape's real strength is its ability to take an integrated, holistic approach', suggesting that there is a way to understand 'the complex interactions between natural processes and human life—between natural, economic and social capital' [37]. On first reading, this appears to be a way of bridging the gap between general and specific; however, the report's response is to immediately shift down to the detail-level of material specification, tree planting, and the placement of renewable energy sources, for example. However, hidden in the text is a short phrase that these authors consider to have the potential to transform the way that landscape and landscape design are contextualised within policy and guidance and to span the conceptual void between general and detail: 'Perhaps most importantly, landscape professionals can create a vision for an environmentally sound future' [37].

Moore [3] and Nikologianni et al. [40] identified the need for a strong vision and leadership in order to drive change at scale without losing impetus when translating big ideas into detailed responses. The case of Birmingham's City of Nature (below), with its reference to the vision for a West Midlands National Park [41] and the examples of the Landscape Observatory and Room for the River are cases in point. This guidance is represented by a split block: the smaller block relates to government guidance, and the larger block demonstrates how this industry works at a range of scales with varying degrees of detail (Figure 4).



Figure 4. Landscape Institute, Landscape for 2030 spectrum evaluation.

4.3. Birmingham City Council—City of Nature

As part of the national Future Parks Accelerator programme running across eight UK cities, Birmingham's City of Nature instigated an 'exciting conversation on how the city treats its natural environment and how it thinks about the future of its parks and green spaces' [42] in response to the 2016–2017 Parliamentary Inquiry [43] on Future of Public Parks. The city of Birmingham was built on the 2013–2018 Liveable Cities programme, which concluded with a commitment to systemic change, aiming to examine how a sustainable city could be created and maintained. Initially focused on five key themes: a green city/a healthy city/a fair city/a valued city, and/an involved city, the Council's research revealed unequal access to quality green spaces as the greatest priority in Birmingham's overall response to the climate emergency (a fair city). The resulting environmental justice map [44] combines Indices of Multiple Deprivation with environmental measures, including access to green space, flood risk, and urban heat island effect, to guide the Council's resources towards specific places to achieve environmental justice: 'The fair treatment and meaningful involvement of all people regardless of race, colour, national origin, or income,

with respect to the development, implementation and enforcement of environmental laws, regulations, and policies' [44].

The 2022 City of Nature Plan (CoNP) was written in the context of COP26 and outlines responses to a range of national and regional policies and guidelines with details of how the Plan will be implemented to reflect those broad policies. Of relevance to this paper, the CoNP acknowledges the 'importance of connecting people and nature' [45] as outlined in the 2019 Glover Review of Landscapes, citing the underlying principles of the West Midlands National Park as guiding their response to the landscape. Under the heading of 'A Green City' and in response to the UK Government's 25-Year Environment Plan for 'enhancing landscapes; . . . climate resilience . . . and supporting access to nature for health and well-being' [45], the CoNP identifies nine outcomes that directly position climate and landscape into the realm of policy with implications for how spaces and places are designed, with a budget to establish small-scale landscape enhancement activities:

- A complete change in how we build our public realm is required, providing improved connectivity and supporting the restoration and viability of urban areas.
- Green corridors that are easier to find and use help citizens use them for active travel, thereby improving air quality.
- An enhanced network of green spaces and green infrastructure that are safe, clean, sustainably managed, and meet the Birmingham Fair Parks Standard.
- The restoration of green spaces, nature, and the environment.
- Greener development brings natural landscapes or features into every place and neighbourhood.
- Opportunities to help citizens make better use of green spaces outside their homes for growing food or communal gardens.
- The Nature Recovery Network stretches across the city and links with all our West Midlands neighbours, forming part of the West Midlands National Park.
- An increase in tree canopy coverage across the city will be mae to 25% through the Birmingham Urban Forest Master Plan.
- A change to the city's governance structures that oversee the city's natural environment over the full 25-year term.

Of perhaps greatest significance is the development of a governance model to support the successful development of all proposed strategies by the CoNP. The model comprises a Board, a Steering Group and an Operations Group, which together form the Alliance, established to act appropriately to improve the integration of services and achieve 'wider recognition of the value of preserving and improving the city's natural environment' [43]. The significance comes from the close links established between the programme's governance structure and the council's leaders through this Alliance, a collaboration across council departments and directorates in conjunction with third-sector partners. This new and innovative governance model required mutual agreement across the wider City Council and programme partners and ensured that matters pertaining to nature in the city were considered across directorates, identifying 'the need to integrate the role and function of the natural environment [. . .] into central decision-making'. This guidance is represented by an equally split block: that on the left is larger than those above, demonstrating that responds to a greater breadth of policy (economic, health, climate, etc.), and the block to the left of the intermediate scale represents a city scale (Figure 5).



Figure 5. Birmingham City Council, City of Nature spectrum evaluation.

4.4. The Landscape Observatory—Catalonia, Spain

Since 2005, the Landscape Observatory (LO) has developed several landscape charters and plans in Catalonia and is recognised as an advisory body on landscape issues for the Government of Catalonia and Catalan society. Initially established to implement the European Landscape Convention (ELC) and landscape agenda in Catalonia, it has been successful in bringing attention to the land and creating a landscape-oriented culture. Structurally, the LO is organised as a consortium, which is included in the Act for Protection, Management, and Planning of the Landscape in Catalonia [46]. The LO has formalised the identification of the regional landscape, recognising its value from a professional and political perspective, as well as its connection to the community. One of its flagship projects is the creation of Landscape Catalogues, tools that cover all of Catalonia and define the landscape character, values, and objectives of each component territory. A key element for their success and impact is that 'the catalogues started with an integrated vision of the landscape that takes the natural and cultural components jointly, never separately' [47]. Several of the LO's projects deal with the value of the landscape, its place and significance in local policy, and its impact on the community, including the 'La Cerdanya' project. This is a map expressing the character and quality of the area, together with future possibilities for the landscape. Demonstrating the spatial quality of the region through high-quality maps impacted how the landscape was seen by professionals and decision-makers who could then articulate strategies and values for the future of this landscape. Following the impact and success of the Cerdanya project (initiated in 2015), the Andorran landscape and its National Landscape Strategy were initiated in 2019 and first published in 2022. A collaboration between the LO and the Andorran Government resulted in the development of a National Landscape Strategy for 2035 [48], producing a map based on the strategy, quality objectives, actions, and aspects of the Andorran landscape.

Combining spatial and policy projects has allowed the LO to play a leading role in the understanding and exploration of a landscape vision by decision-makers, professionals, and the public. The LO has changed perceptions of the landscape in the region and is recognised as a best-practice example internationally, with the Observatory's strategies and spatial landscape ideas (catalogues, maps, etc.) having a direct impact on policy and governance beyond the scope of the region alone. The work conducted by the LO has a strong conceptual basis and is recommended at a detailed level. However, this project also deals with climate change policy at a landscape scale, albeit not wholly joined up across all scales. (Figure 6).

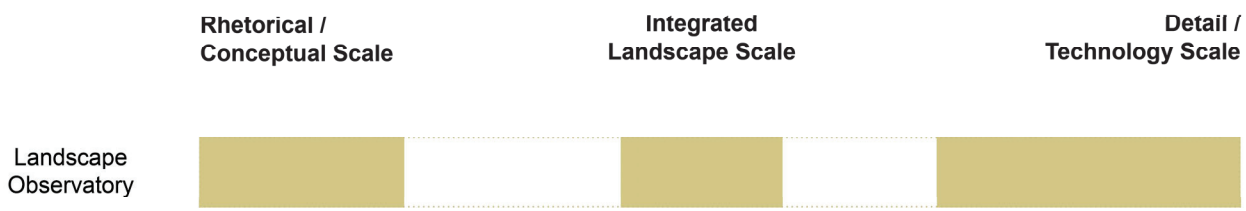


Figure 6. The Landscape Observatory spectrum analysis.

4.5. Room for the River—Netherlands

'Room for the River' is a national landscape-led scale programme in the Netherlands that deals with landscape, spatial planning, climate change, hydrological efficiency, the rise of water levels, and quality of space. The programme created methodologies to address water safety and climate emergencies (rising sea levels) while providing the nation with an enhanced landscape. As a demonstration of climate-driven regional landscape design, it enabled renewed space for the river to flood safely in 34 locations across the Netherlands. This national programme addresses the climate crisis through spatial strategies by integrating a strong conceptual vision with the creation of policies and legislation to support its aims. Room for the River has a collaborative agenda, allowing local authorities, national governments, professionals, and the public to work together on the same issue, backed up by a new project management structure integrated into policy and decision-making. This integrated vision achieved a complete shift in the existing water management policy, which was brought about by presenting stakeholders with a clear vision of the nation's landscape quality, character, and environmental characteristics [49]. The Room for the River Programme is one of the most well-developed, national-scale, landscape-led programmes to date. As shown in Figure 7, all three pillars are developed to an advanced level, running from one to another. The conceptual scale has been developed for the whole programme, setting specific goals that have been delivered both at a regional and local scale. The Technological scale of the programme is quite advanced, with the concept being infused into the delivery. Both sides of the spectrum are connected with the Integrated Landscape Scale, making room for the River project significant from both policy and environmental perspectives.

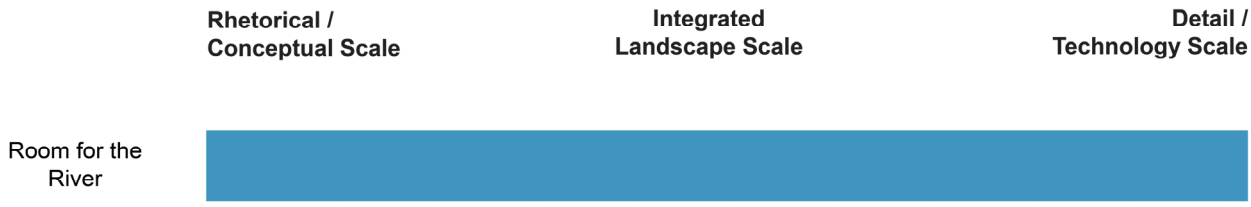


Figure 7. Room for the River spectrum evaluation.

The European case studies outlined above demonstrate that with a clear, integrated vision, the impact and effects of climate change and environmental sustainability can be embedded in landscape policy and guidance. Generalised targets, while crucial, tend to be interpreted as generic technological solutions with little or no spatial or cultural consideration.

5. Discussion

In the two European programmes presented above, clear and compelling visions for specific landscapes have been rendered visually with maps and spatial diagrams. These rhetorical-visual-spatial devices drive policy and strategy at a high-level political scale and can be interpreted by landscape designers and planners at the specificity of a local site scale. For the Landscape Observatory and Room for the River case studies, the political dimension has facilitated the concept or implementation of the landscape project and has had a significant impact on decision-making and political actions in relation to the landscape design. For large-scale climate and sustainability issues, policies and guidance play a crucial role in securing the delivery of such concepts. In cases where the support of decision-makers and politicians was prominent, landscape-led approaches thrived, having a significant impact on the wider area and community. For the Landscape Observatory and Room for the River projects, landscape qualities, values, and objectives have been

made culturally visible within current and upcoming policies to the point that they are now interwoven into the legislitave fabric of the regions. Legislation established in the Netherlands and Catalonia allows for the open discussion of environmental, biodiversity, and landscape values, embedding a broader and more holistic approach to landscape design and planning at the regional level. Catalonian Law 8/2005 of 8th June (Decree 343/2006) 'establishes that, once the landscape catalogues, classification, and characterisation have been approved [. . .] they will be incorporated in a regulatory way as landscape directives [. . .] in the territorial masterplans that the Ministry of the Territory and Sustainability considers appropriate, after public consultation' [47]. Laws relating to landscapes should act as guidance to ensure the delivery of a landscape vision and its key qualities. In the Netherlands, Room for the River has significantly shifted national policy—'the old policy was based on discharging surplus water to the sea as quickly as possible, the new policy became to first retain water, then store the water, and finally discharge the excess water. The new water policy was later linked to nature development and implementation of the EU Water Framework Directive'— the European Climate Adaptation Platform [50]. Although the focus is on water management, the wider scheme integrates measures to address sustainability and the climate emergency from the generalised high-level policy down to the site scale through the use of spatial strategies for the landscape. The observations made by these case studies point to the impact of policy/guidance in a regional landscape strategy, which has helped to ensure integration within the vision and narrative of the project, as well as supporting its delivery in more sustainable ways. The Landscape Catalogues produced by the Catalonia Landscape Observatory provide rigorous detail about the unique qualities of the Catalan landscape and have had a substantial response from the Catalan Government [51], leading to broader projects dealing with regional and national landscape strategies with the support of neighbouring French, Catalan, and Andorran governments. Mulugetta and Urban [52] state that 'there is no alternative for countries but to incorporate low carbon measures in their development policies. The reality of climate change demands it, and there are also clear benefits in pursuing such policies'.

In both European case studies, the projects were driven by a vision for a better landscape future, which was expressed through high-level political rhetoric and commitment, articulated spatially using quality maps and diagrams, and interpreted through design by landscape professionals into site-appropriate technical solutions using the medium and material of specific landscapes. As illustrated in Figure 8, these clearly articulated visual-spatial landscape strategies span the void between generalised high-level political commitments and the detail of technical solutions, completely in the Room for the River project and partially in the Landscape Observatory [3]. The three UK guidance documents illustrate the effects of the polarised situation. The Natural England and RSPB document effectively articulates the issues that need to be addressed to deal with the effects of climate change and associated environmental degradation and offers practical, tested solutions for adaptation and mitigation at a detailed level. However, there is no spatial strategy for this approach, and given the remit of the oorganisation, the landscape is reduced to its natural and physical components with little consideration of the social and cultural aspects. The Landscape Institute's document outlined above covers a broadly similar approach, with high-level aims that are rendered as site-level technical solutions. It is encouraging that the LI recognises that landscape professionals have a role in creating 'a vision for an environmentally sound future', and we welcome the opportunity for further study and development of such a vision, which must, by our reckoning, span the rhetorical-spatial-visual middle ground of words and images, maps, and diagrams, as described by Kathyn Moore [3]. Birmingham City of Nature Plan comes closest of the three documents studied in articulating an integrated vision for a sustainable future for a specific place. A clear

vision backed up with innovative cross-sector governance; however, it still lack the visual and spatial devices modelled by the European case studies.

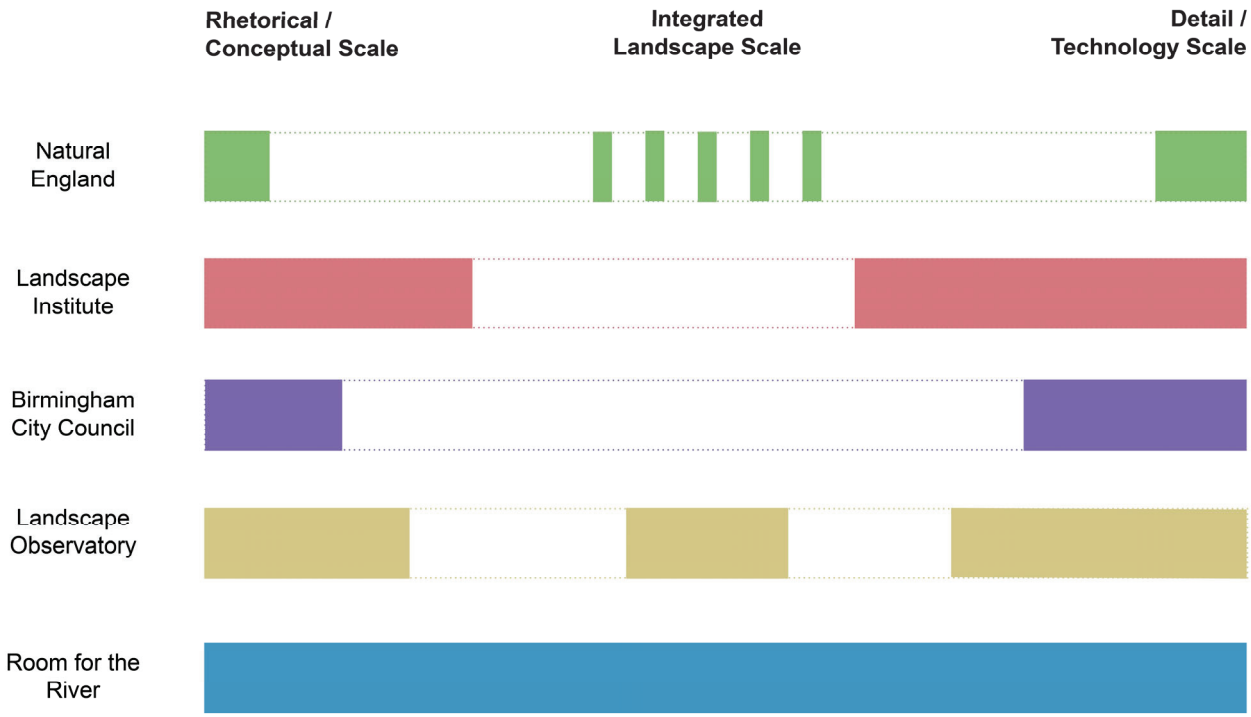


Figure 8. Comparative case study spectrum evaluation.

In all three UK documents, the landscape is dealt with in a piecemeal way. Monitoring, intervention, and design are at a site-by-site level, which is a result of demarcation and delineation. This spatial fragmentation implies that landscape-scale spatial strategies are rare because land is fragmented by ownership and responsibility. There is little political impetus for a spatial strategy because high-level targets are passed down the food chain for smaller agencies, institutions, and individuals to work within the smaller and smaller boundaries of individual sites. This is why we tend to see policy and guidance for climate and sustainability in landscape and landscape design clustering around site-specific technological solutions illustrated by case studies rather than vision-led landscape-scale approaches such as the Landscape Observatory. There are exceptions, with landscape visions such as the Colne Valley Regional Park [53], River Rea Landscape Vision [54], and the West Midlands National Park being commissioned and published, which are by various means influencing policy and guidance relating to climate and sustainability for landscape, with implications for design. This study emphasises the importance of a holistic approach that has the support of decision-makers and is backed by appropriate policy. We have shown that landscape-led schemes, especially when integrating all the necessary steps (such as conceptualisation, climate elements, policy, technological solutions, and community engagement), have the most impact on linking environmental guidance with landscape design at scale.

6. Conclusions

There is a separation and polarisation between high-level statements, targets, and commitments to address climate and sustainability and detail-oriented site-specific technological solutions to such targets. Guidance pertaining to landscape professionals tends to cluster around the 'detailed' end of this spectrum, perpetuating the false notion that, due to the UK's fragmented land ownership, there is no need for a landscape-scale spatial strategy

and vision. This is compounded by the separation of the landscape into distinct and easily monitored 'assets' rather than being considered as the relationship between communities and their territory, the vast physical and cultural infrastructure upon which we depend for everything. Where professional guidance exists, there is a need to consider if and how to translate this into enforceable policy as part of a wider programme of 'creating a vision for an environmentally sound future' [4].

Strong visions for a sustainable future already exist in the hundreds. What we need are those that are truly 'down to earth', appropriately situated in the landscape, and expressed through political commitment. They should be articulated spatially using quality maps and diagrams and interpreted through design by landscape professionals into site-appropriate technical solutions using the medium and material of specific landscapes.

The role and importance of landscape beyond its physicality (expressed through carbon and biodiversity targets, for example) are not represented in current legislation or guidance, either at strategic or more detailed levels, such as designing new spaces, preserving existing places, or the importance of community resilience. We join the call for a landscape strategy that encompasses its entirety, from the 'everyday' urban landscape to those marked as special, and acknowledges its material, cultural, economic, and ecological facets. Policy, systemic change, and embedding environmental and climate visions in strategic spatial plans will have tremendous benefits if applied to the design and planning processes.

Achieving a de-polarisation of climate and sustainability guidance applicable to landscape design requires the integration of vision, leadership, and governance, backed up by policy to make it happen, and guidance to demonstrate how, through design, transformation can happen.

Future Recommendations

In this article, we evaluated a number of documents to help articulate an emerging line of enquiry. Further studies should incorporate a comprehensive survey of policy and guidance documentation to illustrate the observed polarisation more clearly. New case studies that occupy the gap between 'generalisation' and 'detail' should be investigated, with a particular focus on the rhetorical-spatial-visual devices of maps, diagrams, and images as the means by which visions are located and communicated.

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Review

Expansion of Lifestyle Blocks in Peri-Urban New Zealand: A Review of the Implications for Environmental Management and Landscape Design

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Abstract: Lifestyle blocks (LBs) are small rural holdings primarily used for residential and recreational purposes rather than commercial farming. Despite the rapid expansion of LBs over the last 25 years, which has been driven by lifestyle amenity preference and land subdivision incentives, their environmental performance remains understudied. This is the case even though their proliferation is leading to an irreversible loss of highly productive soils and accelerating land fragmentation in peri-urban areas. Through undertaking a systematic literature review of relevant studies on LBs in New Zealand and comparable international contexts, this paper aims to quantify existing knowledge and suggest future research needs and management strategies. It focuses on the environmental implications of LB activities in relation to water consumption, food production, energy use, and biodiversity protection. The results indicate that variation in land use practices and environmental awareness among LB owners leads to differing environmental outcomes. LBs offer opportunities for biodiversity conservation and small-scale food production through sustainable practices, while also presenting environmental challenges related to resource consumption, greenhouse gas (GHG) emissions, and loss of productive land for commercial agriculture. Targeted landscape design could help mitigate the environmental pressures associated with these properties while enhancing their potential to deliver ecological and sustainability benefits. The review highlights the need for further evaluation of the environmental sustainability of LBs and emphasises the importance of property design and adaptable planning policies and strategies that balance environmental sustainability, land productivity, and lifestyle owners' aspirations. It underscores the potential for LBs to contribute positively to environmental management while addressing associated challenges, providing valuable insights for ecological conservation and sustainable land use planning.

Keywords: biodiversity conservation; environmental sustainability; greenhouse gas (GHG) emission; highly productive land; land use change; landscape strategy; smallholding

1. Introduction

1.1. Peri-Urban Pressure and the Rise of Lifestyle Blocks in New Zealand

Much of New Zealand (NZ)'s highly productive land (Land Use Capability [LUC] classes 1–3) is increasingly threatened by expanding urban development. Figure 1 shows that between 2002 and 2019, the area of productive land lost to housing development rose by 54%, while the area of rural residential land increased by 109% [1,2], contributing to further fragmentation of the remaining productive land [2]. This trend threatens the spatial

continuity and ecological integrity of peri-urban landscapes by converting urban–rural land into low-density residential development. It also compromises its capacity for both food production [3] and ecosystem services [4]. There is therefore a need for carefully considered strategic planning in these important peri-urban areas.

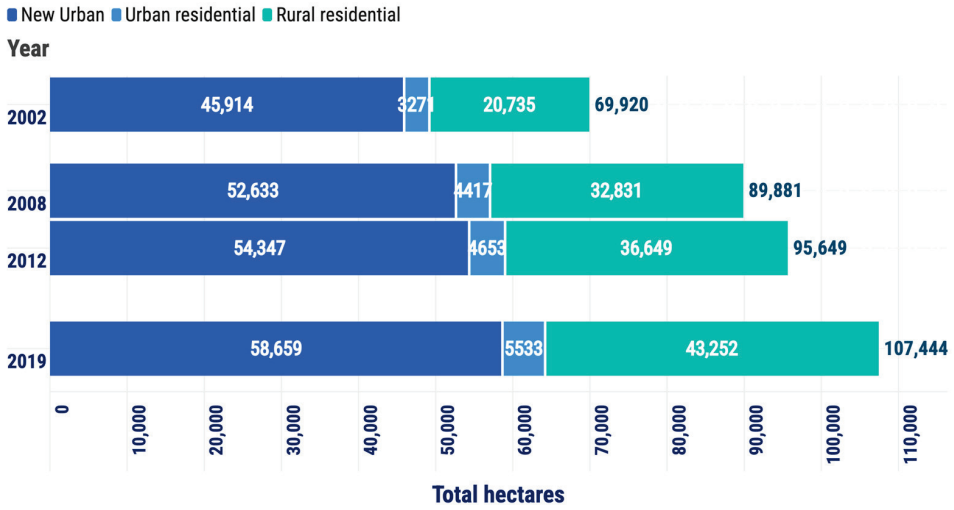


Figure 1. Conversion of highly productive land (HPL) to residential parcels in New Zealand from 2002 to 2019. Source: Figure created by the author based on data from Stats NZ [2].

Over the past decades, a prominent characteristic of peri-urban development in New Zealand has been the conversion of rural or previously agricultural land, driven by the demand for lifestyle living and the financial gains from rural subdivision into lifestyle blocks [5–7].

1.2. Lifestyle Block Definitions

Lifestyle blocks (LBs), also known as hobby farms or lifestyle properties, are a subset of smallholdings—semi-rural properties not primarily used for commercial farming that typically emphasise residential and lifestyle use. In NZ, LBs have become a prominent feature in the peri-urban regions [5–10], accounting for 3.55% of the total national land base [11]. By comparison, despite having expanded rapidly in recent decades, urban land still only covers under 1% of New Zealand's land mass [2]. Land Information New Zealand (LINZ) describes LBs as "generally in a rural area, where the predominant use is for a residence and, if vacant, there is a right to build a dwelling. The land can be of variable size but must be larger than an ordinary residential allotment. The principal use of the land is non-economic in the traditional farming sense, and the value exceeds the value of comparable farmland" [12].

LB characteristics vary by size, ownership motivation, land use, income level, and farming experience, making them difficult to describe using a standardised definition [5,8,9,13–15].

The main motivations for LB ownership include the desire for clean air, privacy, peace and quiet, open space, and an enhanced quality of life [9,10,16]. LB residents tend to prioritise non-commercial activities such as small-scale farming and gardening interests and self-sufficiency, alongside other recreational activities for personal enjoyment [5,7,8,10,15].

While size definitions vary slightly across regions and studies, both the Environment Canterbury Regional Council [17] and Eade [15] identify LBs as being in a size range between 1 and 20 hectares, with the majority around 5 hectares. Additionally, previous LB studies define an LB as a smallholding property between 0.4 and 30 hectares, with an average size of 5.2 hectares [9,10,16,18].

The essence concept of "lifestyle blocks", which emphasises personal lifestyle aspirations over agricultural productivity and profit, with main income typically derived from off-farm activities, is consistently reflected across international literature from developed countries such as Australia, the United States, and Scotland [19–22].

1.3. The Challenges of Lifestyle Blocks in New Zealand

Less than 15% of NZ's land area is considered to be highly productive land (HPL), making it a finite resource in the country [23–25]. By 2013, however, LBs already occupied nearly 10% of this HPL, with a significant concentration (35%) in the Auckland region alone [5] (see Figure 2). As much of NZ's HPL is located on the urban fringes, it is particularly vulnerable to development pressure from both urban expansion and the growing demand for LBs [24,26,27]. This, combined with a historical lack of clear national direction before 2022, has contributed to the ongoing fragmentation and cumulative loss of this finite resource [24]. Figure 2 illustrates this trend in the Auckland region, where by 2019, 34% of Land Use Capability (LUC) class 1 land, 38% of class 2 land, and 19% of class 3 land had been, or had been earmarked to be, subdivided into small parcels [1].

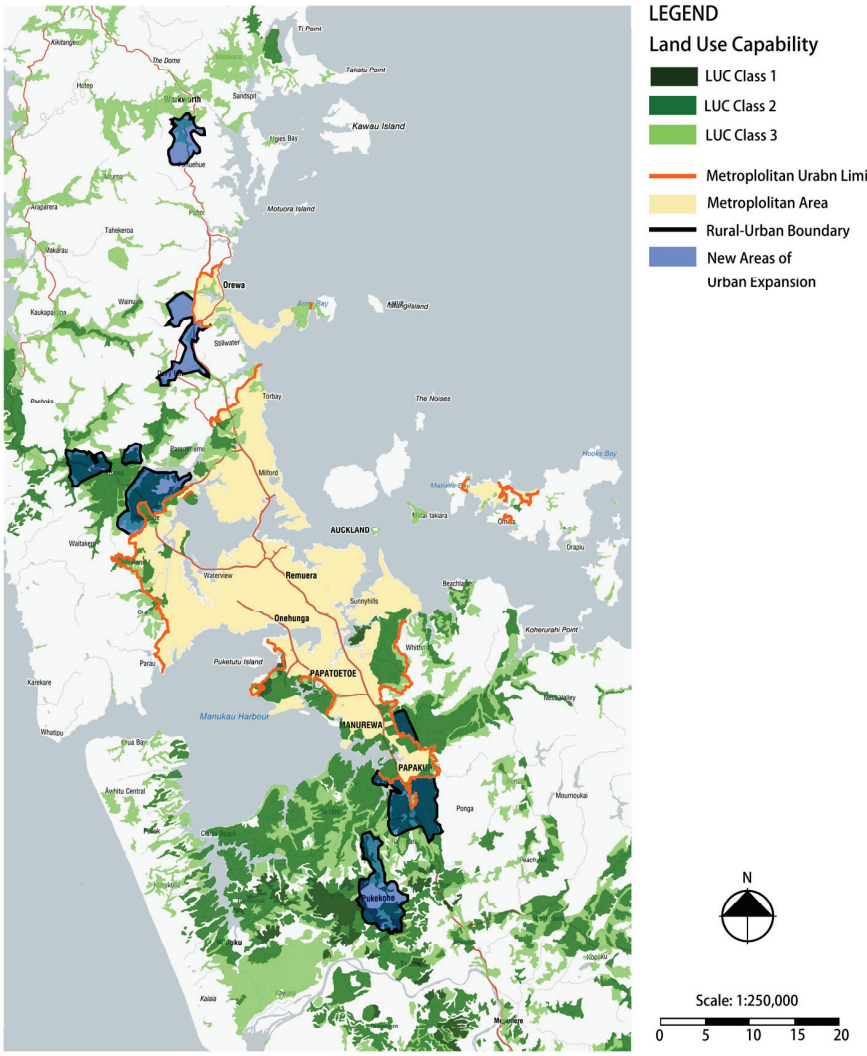


Figure 2. Map of HPL (LUC 1,2,3) in the proposed urban–rural boundary of Auckland. Source: Author's own (2025) elaboration based on data from Manaaki Whenua–Landcare Research [28], Auckland Council [29], Silva [30], and Stats NZ [2].

Moreover, "Small blocks on versatile land are getting smaller from a median of 8 ha in 1970 to slightly under 4 ha in 2018" [15], indicating a continuing trend of HPL becoming more fragmented in NZ. MfE & Stats [25] further reinforced this finding by noting an increase in small-sized parcels (2–8 ha) and a decrease in larger ones (over 8 ha) on HPL during the same period. Increasing subdivision of production land has been seen as a threat to NZ's agricultural land as it could lead to land fragmentation and decrease food security [31–33]. Curran-Cournane et al. [6] note that much of this fragmentation is "largely driven by the desire for rural lifestyle living or hobby farming". Eade [15] agrees with this view and observes that it is likely to continue due to urban pressures such as residential expansion at the rural–urban fringe, competition for land near urban centres, and increasing landowner preferences for lifestyle living. However, this phenomenon has not been without criticism; some farmers have expressed discontent, arguing that the farmland subdivision policies have directly led to the loss of productive land [14,34,35].

1.4. Research Rationale and Knowledge Gaps on Lifestyle Blocks

Although the widespread and growing phenomenon and key challenges of LBs have been recognised, their environmental implications and consequences have received relatively little attention. Previous studies have often been focused on providing general descriptions of property characteristics and ownership motivations, with limited efforts to systematically explore environmental impact. Meanwhile, environmental research and related policies and regulations concentrate more on either urban residential areas or larger-scale agricultural land, leaving a noticeable gap in examining such residential–agricultural mixed land uses like LBs. However, given their "pleasure over profit" nature and increasing occupation of the HPL, LBs have the potential to balance lifestyle with production and conservation via sustainable practices. However, a detailed understanding of their resource use and land management is still insufficient.

1.5. Research Objectives

This paper aims to quantify existing knowledge on the environmental implications of LBs in peri-urban areas through a systematic literature review and highlight areas of research need and management action. It investigates studies about resource use patterns, land use allocation, land management practices, and landscape design strategies. The review also explores both the challenges LBs pose (e.g., land fragmentation, loss of HPL, biodiversity loss) and the opportunities they may offer (e.g., carbon sequestration, sustainable farming, energy efficiency, and water-saving technologies). It also aims to link potential environmental issues associated with LBs to NZ's broader environmental sustainability agenda and provides an international context through reference to international cases in countries such as the United States (U.S.), Europe, and Australia, where LBs or similar developments are also prevalent. In addition, the review offers comparative insights for more effective and sustainable policy-making frameworks for LBs in NZ, drawn from policies and regulations, initiatives, and voluntary stewardship programs that other countries undertake in relation to similar properties.

2. Background

The term "lifestyle block" is recorded to have originated around World War II. Interest in such properties grew markedly in North America during the 1970s with the increase in urban-to-rural migration. Similar land use change trends also spread throughout some other developed countries, including the United Kingdom (UK), Australia, and NZ [19,20,36], though the key driving factors, such as demographics and institutional settings, varied across countries.

In NZ, the emergence of smallholdings and LBs was primarily driven by two factors: the rapidly rising land values under the urban expansion pressure, and the increasing interest in seeking rural lifestyle opportunities [8,10]. This trend has been further encouraged by the key drivers of liberal rural land subdivision policies and regulations, alongside an aging rural population, which has led older landowners to subdivide and sell their land for retirement purposes [8,10,16]. Additional contributing factors include superannuation reforms, declining farming profitability, limited planning policy controls, improved transportation networks, and growing lifestyle preferences for rural amenity and environmental value [8,16,37]. These combined forces have led to the fragmentation of larger agricultural parcels into smallholdings characterised by diverse land uses, including ecological restoration, small-scale farming, rural industries, and LB development [1,5,37]. Such development reflects a complex interplay of agricultural, economic, and socio-cultural changes.

In the early 20th century, rural properties were typically small and aimed towards self-sufficiency, with surplus produce occasionally sold for income [5,15]. Rising agricultural export prices and technological advances during the 1950s to 1970s led to a doubling of rural land values and encouraged land aggregation, resulting in a decline in smaller properties as farming shifted toward larger, more efficient enterprises [5,38]. However, this trend reversed in the 1970s; the sustained inflation in urban land prices affected traditional farmers producing wool, meat, and dairy products, and forced farming diversification in response to the economic challenges, including prompting farmers to subdivide their land. At this time, smaller holdings began to emerge [5,15,19,38]; there were approximately 27,000 smallholdings covering nearly 100,000 hectares in 1976 [14,39]. Smallholdings started to increase significantly from that time on. (See Figure 3). McAloon [38] notes that between 1972 and 1992, the number of holdings below 40 hectares more than doubled, rising by over 130%, reflecting a significant shift toward rural land subdivision and fragmentation. Since the 1990s, due to continuing urban expansion, economic pressure on traditional farming, and the growing ability to subdivide rural land in response to social demand, the number of farms decreased while LBs gained in popularity [5,10,38].

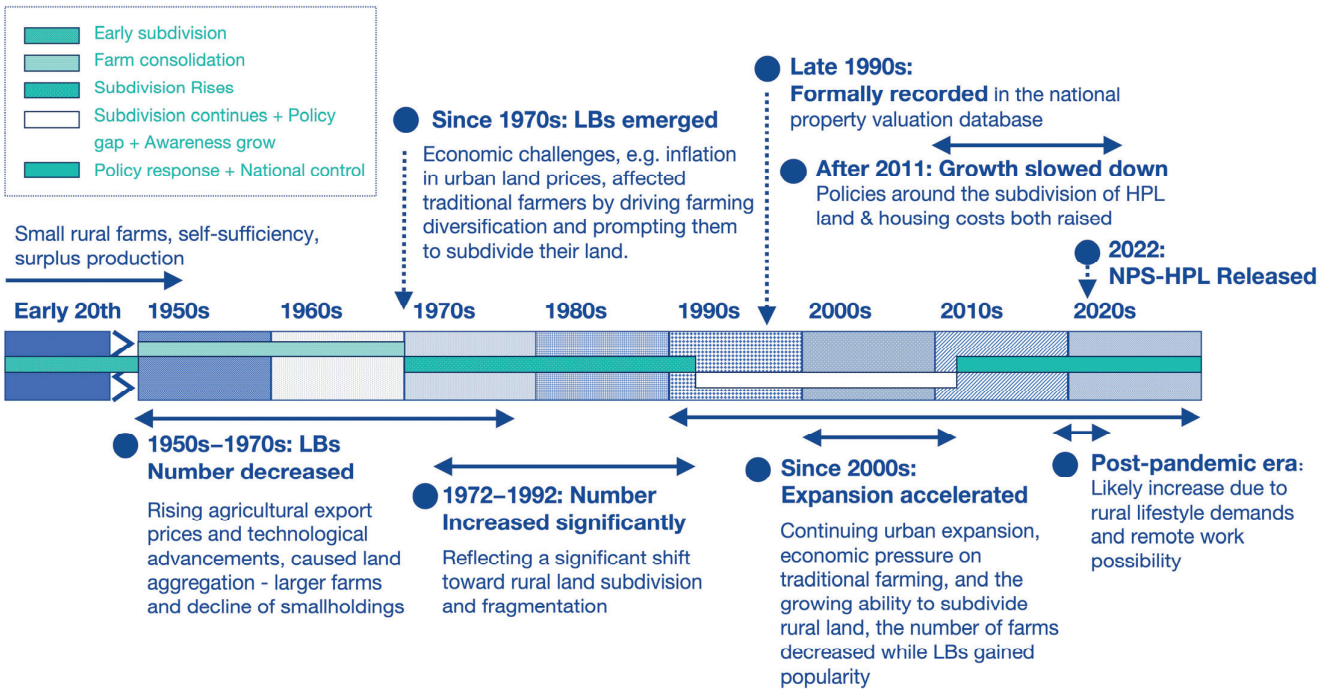


Figure 3. Timeline of the development of LBs and land subdivision in NZ. Source: Author's own (2025).

The number of LBs has been formally recorded in the national property valuation database since the late 1990s [5]. By 1998, the number had increased from an estimated 70,000 to 100,000 [14]. The expansion accelerated in the 2000s–2010s, reaching 139,868 properties (on more than 753,000 hectares) in 2004 [9,10], and growing to 175,000 properties on 873,000 hectares by 2011 [5]. After 2011, the growth rate in LBs slowed down a bit, with over 186,000 properties on nearly 900,000 hectares by 2018 [7]. By 2024, there were 199,429 LBs on 953,000 hectares [11]. This sustained growth is illustrated in Figure 4, which shows the progressive increase in the number and total area of LBs from 1976 to 2024.

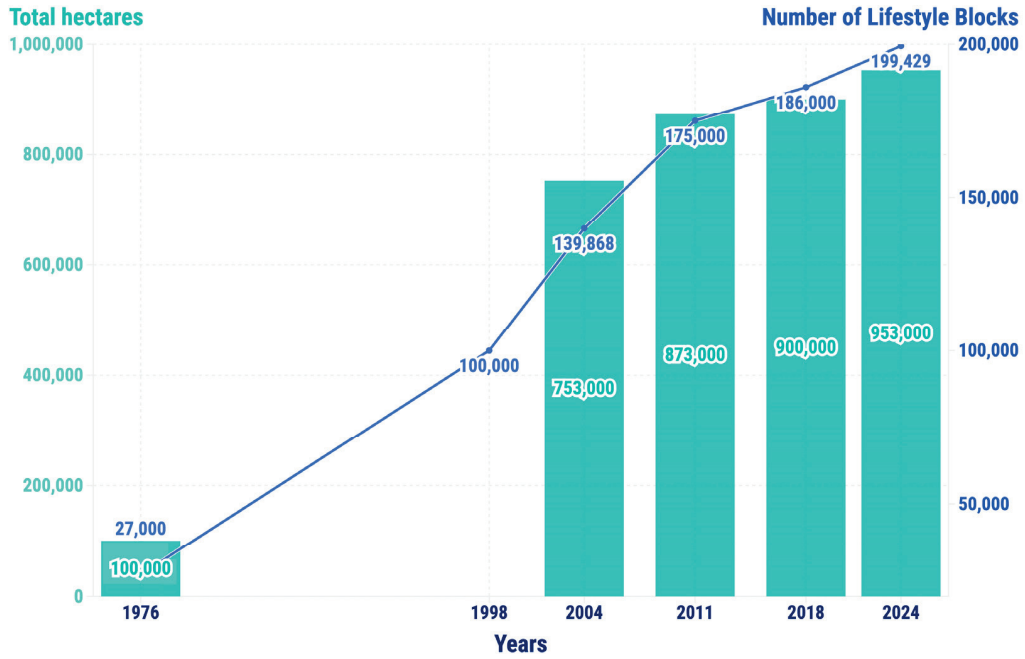


Figure 4. Growth of LBs in NZ from 1976 to 2024. Source: Jowett [39], Swaffield & Fairweather [34], Fairweather & Robertson [14], Andrew & Dymond [5], Pearson [7], and QV [11].

3. Materials and Methods

3.1. Search Strategy

A systematic literature search was conducted in the first quarter of 2025 using Scopus and Google Scholar. These two databases were selected due to their wide coverage of peer-reviewed publications in environmental science, land management, planning, and agricultural disciplines. To complement the academic literature, a separate set of NZ government and regional council documents was reviewed for contextual and policy insights related to LBs, peri-urban development, and land fragmentation. These policy documents were reviewed thematically but excluded from statistical analyses (e.g., country or year of publication) to ensure comparability across peer-reviewed academic sources. Selected doctoral dissertations and conference papers were included to capture emerging research and relevant grey literature, particularly in areas where peer-reviewed publications were limited.

3.1.1. Scopus Search

A keyword-based search was performed in Scopus using the following terms in the title, abstract, and keywords fields: ("lifestyle block*" OR "lifestyle property*" OR "hobby farm*"). This initial search yielded 163 results. A large number of these articles focused on environmental and social issues. Subject area filters were applied to include only literature related to Environmental Science, Social Sciences, Agricultural and Biological Sciences, and

Earth and Planetary Sciences. To maintain contextual relevance, the review focused on studies from NZ and international cases from countries with rural residential development patterns that may offer relevant comparisons. After applying these subject filters and removing duplicates and clearly irrelevant records based on title and abstract screening, a total of 76 articles were retained for full-text review.

3.1.2. Google Scholar Search

Use of the same initial keywords in Google Scholar produced 4060 results, which was considered overly broad and not feasible for manual screening. To refine the results and enhance relevance, a more targeted search string was developed: ("lifestyle block*" OR "lifestyle property*" OR "hobby farm*") AND ("environmental impact" OR "peri-urban"). This reduced the number of articles to 515. To ensure analytical depth in the review of national literature while situating it within a broader global perspective, the articles were organised into two categories: New Zealand-based studies and relevant international literature. To support this distinction, another targeted search string was applied to specifically identify New Zealand-focused studies: ("lifestyle block" OR "lifestyle property" OR "hobby farm*") AND ("environmental impact" OR "peri-urban") AND ("New Zealand"). This search yielded 215 results, forming the core dataset for the national literature review.

3.2. Selection Process

The selection process followed the PRISMA framework (see Figure 5) to ensure a transparent and systematic approach to identifying and evaluating relevant literature. First, a total of 619 records were identified from Scopus and Google Scholar databases (see Section 3.2). After removing duplicates, the remaining records were screened for relevance to the research objectives based on their titles and abstracts. For records with unclear relevance, a quick full-text scan was undertaken to ensure the accuracy of initial screening results. Second, a comprehensive full-text review was conducted to assess eligibility based on predefined inclusion and exclusion criteria (see Section 3.4). Third, additional relevant grey literature was reviewed separately through manual methods, as described in Section 3.2. Finally, all eligible academic and policy sources were retained for thematic coding and synthesis.

3.3. Inclusion and Exclusion Criteria

Articles and documents were selected based on the following inclusion criteria: (a) peer-reviewed journal articles, conference papers, or doctoral dissertations published within the past 50 years, with a primary focus on the period from 2000 to 2025. The choice of timeframe to study corresponds to a notable acceleration in LBs since the 2000s. An examination of more recent studies can also better reflect current land use changes and environmental concerns. Articles were also selected based on (b) content addressing environmental issues, land use, sustainability in the context of lifestyle blocks, lifestyle properties, hobby farms, smallholdings, or similar peri-urban rural properties such as non-commercial farms. Only studies that examined or included relevant cases from New Zealand, Australia, the United States, Canada, or the United Kingdom were considered, given the comparability of their socio-environmental and land use conditions.

The exclusion criteria included the following: (a) studies unrelated to environmental sustainability or land management (e.g., studies in computer science or engineering), as well as (b) those based in countries with significantly different socio-economic and land use conditions compared to NZ (e.g., densely urbanized or high-intensity agricultural regions in countries such as China, Japan, or India). (c) Publications that focused solely on large-scale commercial agriculture or lacked relevance to small-scale, non-commercial land use settings (e.g., lifestyle blocks or smallholdings) were excluded. (d) Duplicate

records, (e) inaccessible full texts, (f) grey literature without clear relevance, (g) non-English publications, and (h) publications prior to 1975 were removed from consideration.

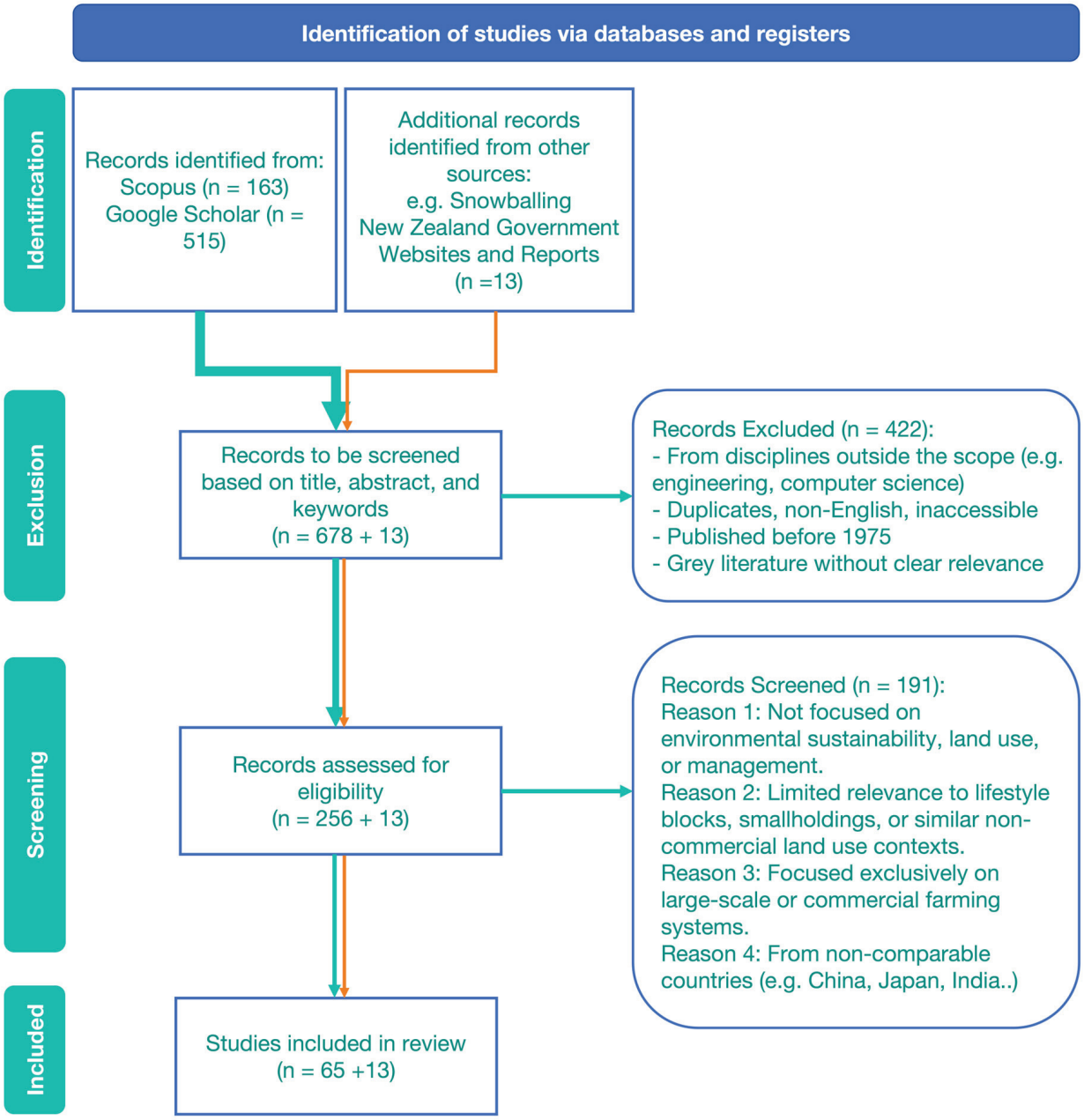


Figure 5. PRISMA model. Source: Author (2025).

3.4. Output

Following the selection process, a total of 65 academic publications were retained after full-text screening. In addition, 13 national and regional policy documents and government reports were reviewed separately from academic journal articles to distinguish practical policy from scholarly research. This resulted in 78 sources for further analysis. Of these, 42 articles focused on New Zealand, while the remaining 36 represented international cases from comparable countries. A full list of the reviewed sources is provided in Appendix A.

3.5. Study Characteristics and Distribution

Most of the literature was focused on New Zealand and Australia, where LBs are widespread and considered significant in land use change (Figure 6). However, despite

increasing attention in recent years, systematic assessments of LBs' environmental impacts are still limited, and there is a lack of in-depth investigation. Studies from New Zealand account for over half of the total, reflecting the importance of LBs as a subject in the country's land use and environmental research. Australian studies highlight the clearing of native bush and forests for LB development, raising concerns about habitat loss and threats to endangered species [37]. They also address related issues such as land fragmentation, natural resource management, and amenity-driven rural migration. Additional studies were mainly identified from the US, the UK, and Canada, where rural subdivision patterns, socio-environmental challenges, and hobby farming practices show notable similarities with those in NZ. Cross-country comparisons highlight shared patterns of LB development and their relevance to international policy discussions and comparative case studies. While most of the literature is country-specific, a number of articles have conducted cross-regional or comparative studies [5,20,37,40].

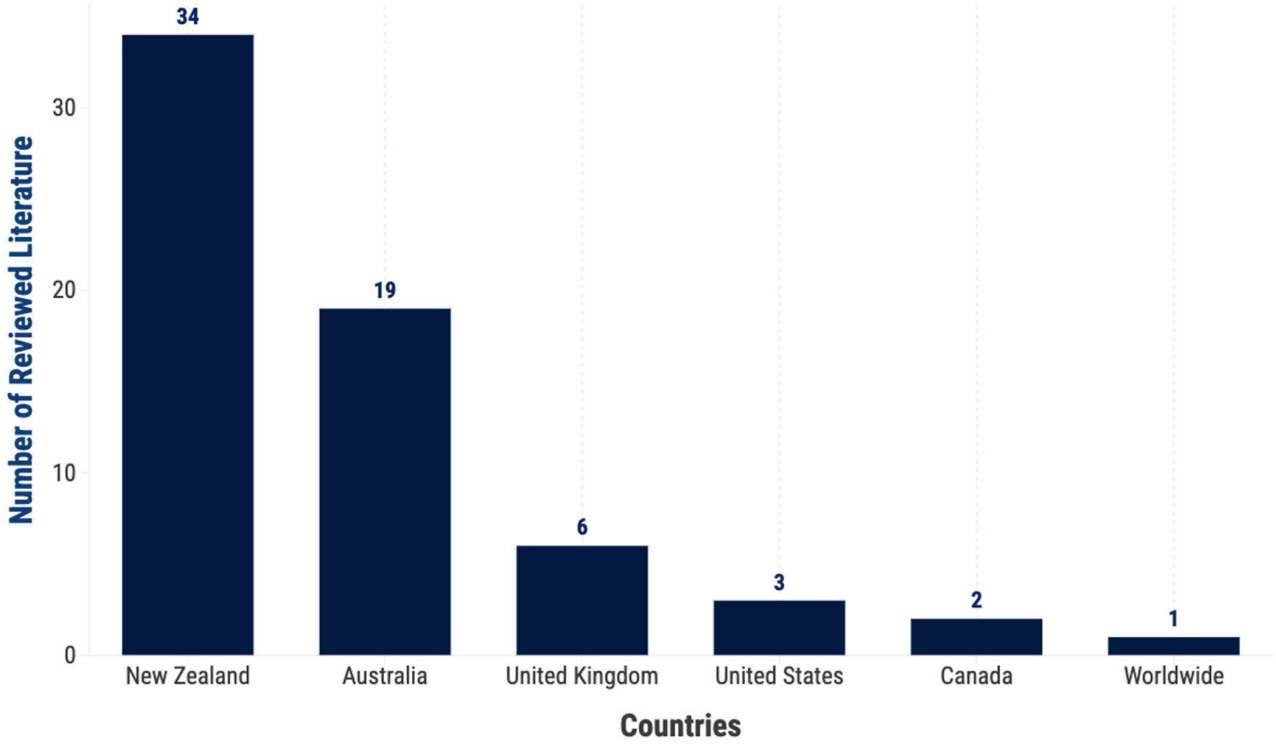


Figure 6. Distribution of reviewed literature by country. Source: Author (2025). Note: The 13 NZ policy documents were excluded to ensure consistency across peer-reviewed sources and avoid inflating NZ's representation.

In terms of publication timeline, the reviewed literature spans from the 1980s to 2025, with a notable increase in output over the past two decades. As shown in Figure 7, academic attention to LBs began to increase in the early 2000s, coinciding with the accelerated expansion of LBs during that period. Publication output rose more markedly from the 2010s onward, reaching its peak between 2020 and 2025. This trend reflects the intensified scholarly interest in land use sustainability, ecosystem degradation, and the environmental impacts of dispersed rural living.

3.6. Thematic Categorisation of Literature

To systematically capture the environmental dimensions explored across the literature, thematic coding was conducted to focus on the research objectives, scope, and the terminology used by authors. Five major themes were identified: (1) water resource use and

management, (2) food production and livestock management, (3) energy consumption and carbon emissions, (4) biodiversity conservation and ecosystem services, and (5) regulation and planning policies.

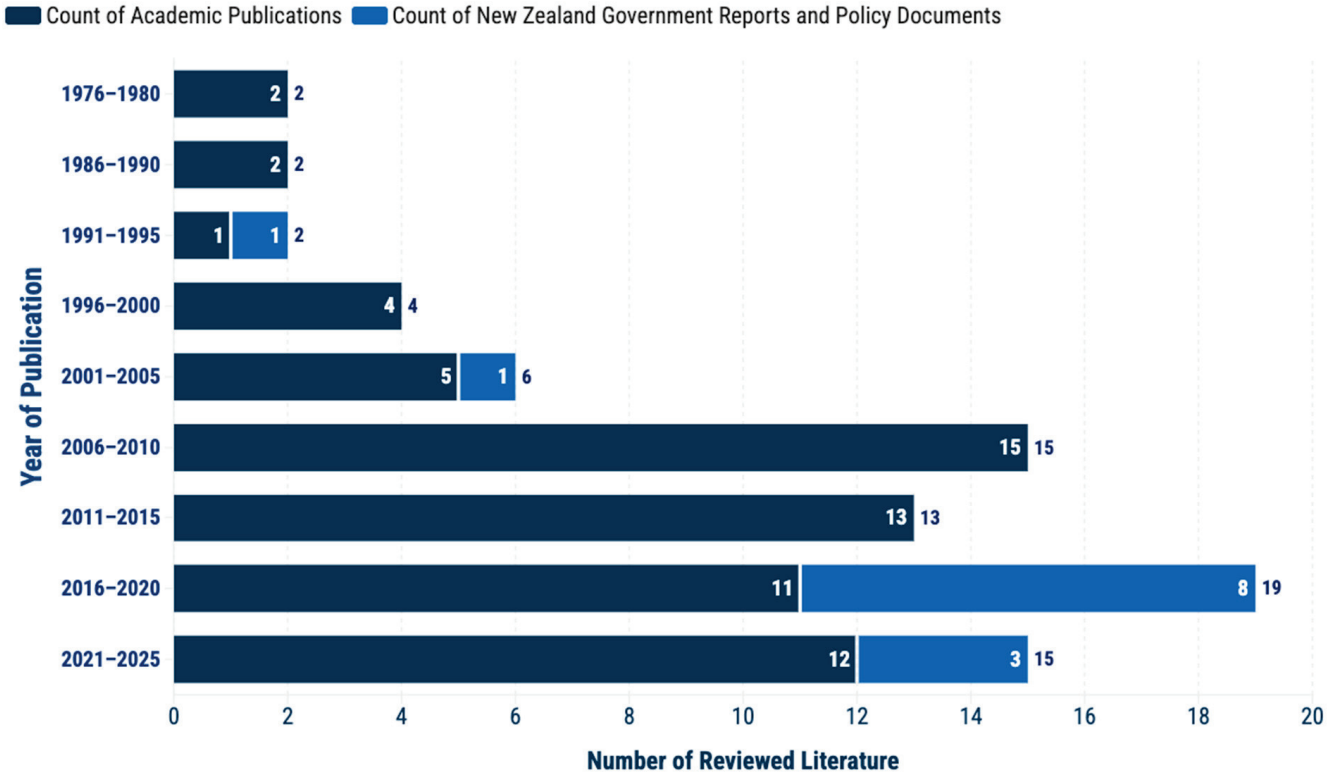


Figure 7. Distribution of reviewed literature by year. Source: Author (2025). Note: The chart includes both academic publications and New Zealand government reports and policy documents.

These categories, further discussed in Sections 4.1.1–4.1.4, illustrate the increasingly multi-dimensional nature of LB development, underscoring both current research priorities and areas where further investigation is needed to support sustainable land management.

4. Results

4.1. Environmental Implications of Lifestyle Blocks

Over time, the focus of LB research has shifted. Early studies (1980s–early 2000s) mainly explored demographic characteristics, motivations, land use patterns, and lifestyle choices of LB owners, along with rural land fragmentation and related planning challenges. Since the 2000s, as LBs expanded, research attention has turned toward environmental concerns, particularly the occupation of HPL and pressures on food production, natural resources, and ecosystems. This shift reflects a growing recognition of LBs as not only socio-economic phenomena but also key drivers of environmental change in rural and peri-urban landscapes.

The continued expansion of LBs has resulted in a range of environmental impacts, including land fragmentation, the loss of highly productive farmland, habitat degradation, and reduced populations of indigenous species [41], with consequences for soil health, food production capacity, water systems, and biodiversity [26]. Andrew and Dymond [5] and Curran-Cournane et al. [42] also highlight the irreplaceable and irreversible impact of converting high-class agricultural land into lifestyle or urban subdivisions, noting that such conversion reduces productive capacity due to fragmentation and the loss of scale required for efficient farming. Once land is subdivided for residential use, it is rarely restored to

productive agricultural purposes, especially when permanent infrastructure such as roads and buildings is in place, making the change effectively irreversible.

From an international perspective, studies such as those by Andrew and Dymond [5] and Song et al. [43] observe a significant and growing trend of LB development in peri-urban regions, particularly in developed countries like Australia, the U.S., and the UK. This expansion has raised similar concerns around land fragmentation, environmental pressures, and the loss of farmland, as subdivision disrupts contiguous agricultural land and undermines local food production capacity [20,40]. Furthermore, studies such as that by Cook and Fairweather [10] found that smallholders generally show limited engagement in chemical management, soil and water quality monitoring, native vegetation growth, and organic farming initiatives, resulting in modest contributions to environmental sustainability compared to traditional farmers.

Despite these concerns, several studies identify potential opportunities for LBs to enhance ecological and food system outcomes. For instance, Hart et al. [44] acknowledge benefits such as improved water quality from reduced intensive farming, enhanced biodiversity protection on private land, and the revitalisation of rural communities through increased population and economic activity. Positive environmental outcomes may also result from collective land management, ecological restoration, and a shift away from conventional farming practices [44,45]. Similarly, Polyakov et al. [22], Pearson [7], and Our Land and Water National Science Challenge (OWL) [46] emphasise the environmental value of planting native trees and establishing green corridors, which can address habitat fragmentation and promote ecological connectivity. Song et al. [43] argue that LB owners can play a key role in the multifunctional transition of peri-urban landscapes by preserving green space and practising sustainable land management, thereby potentially reducing the fragmentation pressures. In terms of productivity, small-scale farming on LBs can help reduce food miles and strengthen resilient local food systems. With appropriate support and flexible land use arrangements, practices such as regenerative grazing and high-value horticulture (e.g., organic kiwifruit orchards) can enable LB owners to contribute positively to both environmental and economic outcomes [15].

Beyond land use and biodiversity, the broader water–food–energy–biodiversity nexus is increasingly recognised as central to understanding the sustainability of LBs at the household level [47–49]. As integrated systems of living, production, and consumption, LBs influence both biophysical conditions and household resource use. These interrelated dimensions call for a holistic perspective on LB sustainability. Accordingly, the following sections examine key domains of environmental impact and opportunity, including household consumption patterns in water and energy use, food systems, and biodiversity management.

4.1.1. Water Resource Use and Management

Cook & Fairweather [10] identify water scarcity as one of the most important issues among LB communities. LBs generally have a strong dependence on natural water supplies such as rainwater, groundwater, and streams, which makes them particularly vulnerable and sensitive to water-related risks like droughts and floods [47]. However, while LB residents demonstrate a strong commitment to conserving water resources [47], their land use activities, such as fertiliser use, livestock overstocking, and poor septic tank management, can place considerable pressure on the quality of freshwater ecosystems [50]. This tension between environmental intentions and actual impacts reflects broader challenges, where technical knowledge gaps, infrastructure limitations, and lifestyle-driven reliance on local water supplies exacerbate risks, particularly in areas with weak governance [51,52]. Several studies addressing water-related issues on LBs are shown in Table 1.

As the number of LBs continues to grow, concerns have been raised over the potential for cumulative impacts. Evidence from Lake Rotorua shows that nutrient leaching and runoff from multiple lifestyle blocks have contributed to water quality degradation [50]. At the same time, Davis et al. [53] argue that the subdivision associated with the growth of LBs in peri-urban areas represents a form of land use intensification, increasing competition for limited water resources and placing additional strain on riparian and groundwater systems. While individual LBs may have relatively low production outputs, their cumulative impact on freshwater ecosystems is considerable.

Recognising these interconnected challenges, policy interventions such as NZ's Freshwater Farm Plans (FW-FPs) have been introduced to guide better land and water management practices, including erosion control, nutrient management, and climate change adaptation [54]. Although currently paused, FFPs can still provide useful guidance for landowners. Regional councils (e.g., Environment Canterbury) also provide practical recommendations and management guidance for LB owners, including advice on regular leak checks, infrastructure planning to prevent runoff, protection of trough valves, and irrigation based on soil moisture levels.

In addition, studies highlight that access to water is becoming increasingly complex and costly for LB owners, which adds another layer of difficulty, as sustainable water use is not only influenced by individual behaviour but also shaped by broader market structures and governance capacity [55]. Furthermore, climate change has exacerbated uncertainties surrounding water availability and further compounds these issues by amplifying the risks associated with drought, flood, and changing rainfall patterns.

Table 1. Summary of studies on water use and management on New Zealand lifestyle blocks.

Author	Year	Methods	Key Themes
Lawrence & McManus [51]	2008	Questionnaire + Interviews (Mixed methods)	Despite strong environmental intentions, households in low-density areas saw little change in water use due to infrastructure limits—water sustainability needs systemic support beyond individual behaviour.
Bay of Plenty Regional Council [50]	2018	N/A	LBs around Lake Rotorua affect water quality through nutrient leaching and runoff, caused by overstocking, improper fertilizer use, and poorly maintained septic systems—showing that even small blocks can harm freshwater ecosystems.
Adeyeye et al. [52]	2020	Case study + Semi-structured interview + Workshop (Qualitative)	Lifestyle-driven water use and reliance on local sources can worsen water marginality where infrastructure and governance are weak.
Robinson & Song [55]	2023	Questionnaire survey + Interviews (Mixed methods)	Growing LBs have increased water demand, but rising costs and complex markets make access harder, showing the need for better water governance to balance lifestyle, farming, and sustainability.
Ministry for Primary Industries (MPI) (Paused) [54]	2025	N/A	NZ freshwater farm plans aim to help farmers, including LB owners, manage risks like erosion, nutrients, and effluent with site-specific actions to improve freshwater quality and support climate change adaptation.
Environment Canterbury [17]	2025	N/A	LB owners are encouraged to manage water wisely by checking for leaks, protecting trough valves, planning infrastructure to avoid runoff, clearing debris from waterways, and irrigating only when soil moisture requires it.
Villamor et al. [47]	2025	Phone survey + Workshops (Mixed methods)	LB owners are generally more concerned about water quality than traditional farmers. They rely heavily on natural water sources like rainwater, streams, and groundwater and are vulnerable to drought. They have less technical knowledge about water systems compared to farmers.

4.1.2. Food Production and Livestock Management

As previously discussed, the expansion of LBs onto HPL has raised concerns about long-term food production capacity and essential soil ecosystem services [5,26,42,56]. Carrick et al. [56] report a further decrease of approximately 50,000 hectares of land potentially available for primary production between 2002 and 2019, largely due to the spread of diffuse rural residential development. This substantial reduction further highlights the threat LBs may pose to regional food security.

Although the MfE and Stats NZ [26] acknowledge the difficulty of quantifying the impacts of land fragmentation and the productivity of LBs, their more recent reporting [26] highlights growing concerns that continued conversion of HPL will intensify pressure on NZ's food production systems. Curran-Cournane et al. [42] express concern that the spread of LBs onto HPL could limit future food production capacity; however, these claims are not supported by direct empirical data, highlighting the need for more targeted research into the biophysical impacts of LB development.

Understanding the actual role of LBs in food and livestock production is therefore critical. As summarised in Table 2, studies by Millar and Roots [31] and Sanson et al. [9] show that most LBs are characterised by low-intensity, diversified production aimed at self-sufficiency rather than commercial output. Typical practices include growing fruits, vegetables, niche crops, and maintaining small numbers of livestock such as sheep, goats, chickens, and cattle, mainly for household consumption or local markets. These systems are often motivated by lifestyle preferences and environmental values rather than financial returns, limiting their contribution to the national food supply but enhancing household resilience and rural diversity. Earlier studies also underline the limited productive role of LBs; for example, Daniels [13] observed that hobby farms and lifestyle properties are generally not focused on large-scale food production and recommended that such developments be located away from prime agricultural land. Sutherland et al. [57] found that non-commercial farms maintain small amounts of livestock and minimal crop production, with some signs of land abandonment, although mixed smallholdings continue to support local food systems. Song et al. [43] and Sise [58] further highlight that while small-scale food and livestock production on LBs is often underreported, it contributes to rural landscape diversity and localised food resilience.

In the Australian context, Millar and Roots [31] noted that although peri-urban regions account for less than 3% of Australia's total land area, they contribute nearly 25% of the country's gross value of agricultural production. While this productivity is largely driven by intensive horticulture, these areas have also seen increasing land use change, including the rise of LBs. Meanwhile, Davis et al. [3] caution that subdivisions onto HPL can intensify land use conflicts and undermine local food systems if not managed sustainably. These findings suggest that the productive potential of LBs depends heavily on owner motivations, management practices, and supportive planning frameworks.

Despite these challenges, there is increasing recognition of the untapped potential of LBs. Eade [15] argues that with effective management, LBs could significantly enhance NZ's local food production without compromising lifestyle aspirations. Strategies such as regenerative grazing and small-scale cropping, tailored to owners' interests, are seen as critical pathways for realising this potential. Similarly, Our Land and Water [46] suggests that optimised use of lifestyle properties could diversify rural economies through small-scale farming, agritourism, and direct sales. Although commercial farming is seldom the primary aim [31], lifestyle properties can nonetheless strengthen localised food networks and enhance regional food system resilience when sustainably managed.

In summary, while LBs are often criticised for inefficiency and the loss of productive land, they also present opportunities to support diversified, small-scale food production

models that align with broader sustainability and resilience objectives, provided that appropriate land use planning and management support is in place.

Table 2. Summary of studies on food production and livestock on New Zealand lifestyle blocks.

Author	Year	Methods	Key Themes
Daniels [13]	1986	Literature review + Case study + Secondary data (Qualitative)	Hobby farms are not oriented toward food production and often keep small-scale livestock for personal or recreational purposes. LBs should be located on lower-quality land away from core agricultural zones to preserve productive farmland.
Sanson et al. [9]	2004	Questionnaire + Literature review + Case study + Secondary data (Mixed methods)	Smallholdings often grow fruit, vegetables, and keep livestock like sheep and cattle for personal use, reflecting lifestyle preferences and sustainable land stewardship.
Millar & Roots [31]	2012	Literature review (Qualitative)	LBs in Australia contribute little to national food output, but occupy high-quality farmland and support small-scale horticulture and livestock for personal or niche use. With proper planning, they may strengthen local food systems.
Andrew & Dymond [5]	2013	GIS-based spatial analysis (Quantitative)	LBs take up a large share of NZ's high-quality farmland, contribute little to food production due to low productivity and non-commercial use, raising concerns about land use efficiency and food security.
Curran-Cournane et al. [42]	2014	GIS-based spatial analysis+ Land use measurement (Quantitative)	High-quality land for vegetables, fruit, and dairy is being lost to urban growth and LBs. While some LBs use pastoral land, few produce food or livestock commercially, posing risks to food self-sufficiency and resilience.
Sutherland et al. [57]	2019	Census data analysis + Typology building + Cluster analysis (Quantitative)	Non-commercial farms (NCFs) typically keep small numbers of livestock, with limited crop production; some show signs of abandonment, though mixed and amenity farms still contribute to food and land use.
Carrick et al. [56]	2020	Indicator analysis + GIS + Spatial overlay analysis (Quantitative)	Reduced capacity for food production on HPL. Livestock-based agriculture is declining as small subdivisions are unsuitable for large-scale livestock operations. Land fragmentation may weaken future food security and rural ecosystem services.
Song et al. [43]	2022	Survey + Semi-structured interview (Mixed methods)	Produce food and raise livestock at small, diverse scales—mainly for self-provisioning or lifestyle reasons. Activities such as fruit growing and cattle keeping support land care, local food systems, and rural landscape diversity through low-intensity, multifunctional land use.
Sise [58]	2022	GIS-based spatial analysis + Survey data (Quantitative)	LBs keep livestock for non-commercial use and now cover a large area in NZ. Though underreported in farm statistics, they may explain much of the missing livestock data. Their food output is small, but their overall impact is notable.
Davis et al. [3]	2023	Survey + Statistical analysis (Mixed methods)	LB subdivisions on HPL cause land use conflicts and threaten local food production. Some owners grow vegetables or keep animals for personal use, large-scale/commercial production is rare. Many value access to local food but raise concerns about environmental impacts and reverse sensitivity.

4.1.3. Energy Consumption and Carbon Emissions

Existing research indicates that, at a household level, electricity use, transportation, and agricultural operations, including livestock management, are among the largest contributors to overall energy consumption and associated greenhouse gas (GHG) emissions [48,49]. On LBs, these patterns present unique challenges and opportunities for sustainable management (Table 3).

Sise [58] finds that many LB owners keep livestock they kept for non-commercial or recreational purposes, and these animals are often not officially recorded in NZ's GHG inventory. The author estimates that this underreporting could result in a 5–8% increase in GHG emissions from beef production and a 1–2% rise in total livestock-related emissions, largely due to unreported livestock. This hidden carbon emission is concerning given that approximately 60% of LBs have beef cattle [18], a sector known for high methane emissions and significant impacts on water and energy consumption. These findings suggest that even small-scale livestock holdings, when aggregated, can exert substantial environmental pressure.

In terms of household electricity use, Qi [59] discusses a typical example of an LB not connected to the public electricity grid, which relies on off-grid solar DC microgrids. In such cases, the use of solar PV systems is emphasised to ensure energy reliability and sustainability, reducing power conversion losses and environmental impacts compared to conventional systems. Qi [59] further emphasises that integrating renewable technologies to meet small-scale demands, such as water pumping and irrigation and animal control systems, can play an important role in reducing emissions from LBs. Transport-related emissions also form a major component of the environmental impacts of LB households. Data from Greater Auckland [60] indicate that peri-urban and rural households, including those living on LBs, typically produce higher transport emissions due to greater car dependence, longer commuting distances, and limited access to public transport. Larger property sizes further amplify electricity use, especially where water systems like rainwater harvesting depend on electric pumps.

Although these trends are increasingly recognised, there remains a significant gap in empirical research specifically examining the energy consumption profiles and carbon emissions of LB households in NZ and internationally.

Table 3. Summary of studies on energy use and carbon emissions in New Zealand lifestyle blocks.

Author	Year	Methods	Key Themes
Sise [58]	2022	GIS-based spatial analysis + Survey data (Quantitative)	Livestock on LBs, though usually excluded from national GHG reporting, could add 5–8% more beef emissions and 1–2% to total livestock emissions.
Qi [59]	2023	Case study	LBs are located in remote areas with limited infrastructure, making it difficult to connect to the public electricity grid. Therefore, the author suggests installing solar panels to address small-scale electricity demands, such as water pumping and irrigation.

4.1.4. Biodiversity Conservation and Ecosystem Services

Regarding biodiversity and ecosystems, in NZ, "private land hosts a quarter of the remaining native vegetation nationwide, including 17% of native forest types that are under-represented in legally protected land" [27]. As Simcock et al. [61] demonstrate, urban expansion and development involve extensive vegetation removal, which reduces the size and connectivity of habitats for indigenous species. In addition, the subdivision of former agricultural or low-intensity rural land to smaller parcels may disrupt local ecosystems, reduce wildlife corridors, threaten biodiversity, degrade soil organic matter, and reduce carbon sequestration capacity.

The research examined showed that LB owners in NZ have demonstrated a strong willingness to engage in biodiversity conservation practice (Table 4). Pearson [7], through a survey in peri-urban Palmerston North, concludes that LB owners actively engage in environmental stewardship practices, such as native planting, improving habitat connectivity, and pest and weed control. As a result, their collective management behaviours could

significantly influence ecosystem services and biodiversity conservation. In an earlier case study, Moller and Moller [45], looking at the Tūmai Beach Sanctuary, explored how LB owners engage with biodiversity conservation and suggested that they are likely to support ecological restoration efforts, which can enhance local landscape ecology and increase property value.

Despite the potential for biodiversity conservation, LBs are also shown to be facing ecological challenges and barriers to effective conservation through woody weed invasion, traditional farming interference (e.g., weed dispersal, effluent pollution, land clearance), and ecosystem degradation [45]. Meurk et al. [4] also stress that without coordinated land use planning and sustainable management strategies (e.g., habitat preservation and stormwater regulation, particularly in fragmented peri-urban landscapes), the positive biodiversity contributions of LBs are easily undermined by ongoing land fragmentation, uncoordinated development, and isolated conservation efforts.

Despite these challenges, more structured support and specialised knowledge in biodiversity aspects need to be considered in LB management. Polyakov et al. [62] emphasise that LB owners in NZ are willing to participate in native forest restoration programs if supported by appropriate incentives. Strategies such as providing seedlings, offering technical support and planting guidance, implementing certification schemes, designing flexible programs, and reducing administrative barriers are particularly effective in encouraging participation. These actions contribute to enhanced ecosystem services, including carbon sequestration, erosion control, and habitat restoration.

Furthermore, according to the Interim Climate Change Committee [63], farms (including LBs) that have post-1989 forests that are at least 1 hectare in size, 5 m in height at maturity, with 30% crown cover and 30 m in width are eligible for the New Zealand Emissions Trading Scheme (NZ ETS) [64]. NZ has lost more small blocks of trees and vegetation (e.g., riparian planting, wetland) that could potentially be counted as carbon sequestration targets than it has gained since 1990 at the national level. The report demonstrates that although joining the NZ ETS would bring challenges to LBs, it would allow conservation and biodiversity protection actions to yield both environmental and financial benefits.

Compared to water management, biodiversity conservation on LBs presents greater challenges due to its dependence on ecological connectivity, complex ecosystem dynamics, and the need for long-term, coordinated management efforts. While water resource interventions can often be effective at the property level, effective biodiversity protection requires collective actions, professional ecological guidance, and sustained policy support to ensure habitat continuity and functional ecosystem resilience.

Research on biodiversity conservation in Australian LBs offers valuable insights and lessons that can be integrated into the NZ context. Song et al. [43] argue that LBs play a vital role in Australia's peri-urban areas, serving as ecological buffers that maintain productivity while preserving environmental values and enabling the coexistence of farming, gardening, and conservation activities. Supporting this view, Polyakov et al. [22] further observe that the value of ecosystem services is maximised when native vegetation covers at least 40% of a property. However, they also report that the current median coverage is only 15% in Australia, highlighting a significant gap and the need for large-scale restoration efforts. In addition, Marshall et al. [65] caution that limited engagement with invasive species management undermines biodiversity goals, and they call for stronger community-based governance. Drawing on these findings, Moller and Moller [45] suggest that, similar to Australia, NZ should also consider increasing indigenous vegetation on LBs to enhance habitats for native bird species [65], improve landscape value, and potentially raise land prices.

Table 4. Summary of studies on biodiversity and ecosystem services in New Zealand lifestyle blocks.

Author	Year	Methods	Key Themes
Moller & Moller [45]	2012	Literature review + Field observations + Case study (Qualitative)	Conventional LBs often exacerbate biodiversity loss and ecological fragmentation, alternative models featuring collective management and ecological restoration, such as Tumai Beach Sanctuary, can enhance biodiversity and ecosystem services.
Meurk et al. [4]	2013	Literature review + Data synthesis (Qualitative)	Supporting biodiversity and delivering ecosystem services (e.g., habitat preservation, stormwater regulation). Risks from land fragmentation if not ecologically planned.
Polyakov et al. [22]	2013	GIS analysis (Quantitative)	Native vegetation on LBs offers amenity and ecosystem benefits, with around 40% cover being optimal. While too much vegetation can limit other uses, most LBs could gain biodiversity and environmental value by increasing native cover.
Marshall et al. [65]	2016	Case study+ Telephone survey + Workshop (Mixed methods)	Less engaged in invasive species control, but essential to landscape-level biodiversity and ecosystem service outcomes. Collective action and community-based governance can improve their integration into conservation and weed management.
Sambell et al. [66]	2019	Survey + Field sampling (Quantitative)	LBs, with mixed vegetation and low-intensity use, support diverse bird species and offer potential for habitat restoration, though outcomes depend on vegetation cover and management practices.
Pearson [7]	2021	Questionnaire survey (Mixed methods)	Strong environmental awareness, engaging in practices such as planting native vegetation for habitat restoration, erosion control, and protecting water quality through riparian planting, especially with community support.
Polyakov et al. [62]	2024	Choice experiment + Questionnaire survey (Quantitative)	LB owners are willing to restore native forests if supported by incentives (e.g., free seedlings, guidance, flexible programs), enhancing ecosystem services like carbon storage and erosion control.
MfE & Stats NZ [27]	2024	N/A	Unmanaged grazing, land fragmentation, and invasive species continue to limit their potential to provide ecosystem services such as habitat connectivity, erosion control, and native species protection.

4.2. Regulation and Environmental Policies Relevant for Lifestyle Blocks

In NZ, although most recent government environmental policies have primarily focused on farmers and farm practices [7], many of these frameworks have since evolved to incorporate LBs, aiming to manage their environmental impacts while recognising their unique land use patterns. Table 5 provides an overview of key NZ policies relevant to or that may impact LBs. The Resource Management Act (RMA) 1991 [67] marked a major shift by introducing effects-based planning and granting local councils discretion over subdivision decisions. Although the Act does not explicitly promote subdivision, it enables the growing process and creates regulatory space for the expansion of LBs, particularly in peri-urban areas.

To address growing land fragmentation, regional councils introduced strategies through Regional Policy Statements (RPSs), aiming to manage unplanned development and designate rural–residential zones to reduce infrastructure costs and land use conflicts [44]. However, systematic monitoring has remained limited, with only a few councils (e.g., Waikato, Auckland, Marlborough) maintaining formal systems to track land use changes, subdivision consents, and pressures on HPL. Recognising the continued risks to HPL, the government introduced the National Policy Statement for Highly Productive Land (NPS-HPL) 2022 [68], which establishes strict land use regulations that significantly impact LBs, peri-urban development, and the management of HPL. It further restricts urban ex-

pansion into peri-urban agricultural zones, ensuring that land-based primary production remains prioritised over residential use. Additionally, the NPS-HPL mandates measures to mitigate reverse sensitivity effects, such as setbacks and buffers, to prevent conflicts between lifestyle developments and agricultural operations.

At the local level, these national objectives are reflected in plans such as the Auckland Unitary Plan (AUP) [29], which encourages LBs to be located within the designated areas such as the "Countryside Living Zone". This zoning approach aims to maintain a low-density rural character while preventing excessive land fragmentation and land use conflict. The AUP also incorporates measures to address reverse sensitivity, such as buffers and setbacks, to manage interactions between LBs and surrounding agricultural activities. By directing LBs away from high-value production zones and into planned rural–residential areas, the policy framework balances demand for rural living with the need to safeguard productive and ecologically valuable land. Curran-Cournane et al. [42] similarly emphasise the need for stronger land use regulations to limit the encroachment of lifestyle development on versatile farmland and ensure long-term land sustainability.

In addition to regulatory planning policies and interventions, national and regional authorities have introduced farm-level environmental management tools to promote sustainable land use on both commercial farms and LBs. Farm Environment Plans (FEPs) [69] have been implemented since the early 2010s in regions like Canterbury to support landowners in identifying environmental risks and developing practices that improve soil, water, and biodiversity outcomes. Similarly, Freshwater Farm Plans (FW-FPs) [54] were introduced through 2020 amendments to the Resource Management Act and are now required under the National Policy Statement for Freshwater Management [70]. These plans apply to a range of properties, including LBs, particularly those over 5–20 hectares or with intensive land uses and require landholders to assess on-farm freshwater risks and adopt practical mitigation measures [54,71].

Incentive-based approaches are also necessary for promoting land stewardship. Morrison et al. [72] highlight that government incentives can encourage LB owners to participate in conservation programs. Building on this, Polyakov et al. [62] show that both financial and non-financial incentives can effectively motivate private landowners, including farmers, livestock producers, and LB owners to engage in native afforestation, with LB owners demonstrating stronger willingness to participate than commercial farmers, as they tend to prioritize biodiversity and aesthetic values over financial returns.

Table 5. Summary of policies relevant to lifestyle blocks in New Zealand.

Policy/Act	Year	Scope	Relevance to Lifestyle Blocks
		National Legislation Law	
Resource Management Act (RMA) [67]	1991/ Amended 2024	An effects-based legal framework for managing land, water, and other resources; promotes sustainable management	All subdivision activities require resource consent (under Section 11 of the RMA); this has facilitated LB expansion in peri-urban areas under council discretion.
Climate Change Response (Zero Carbon) Amendment Act 2019 [73]	2019	A legal framework for setting emissions reduction targets, carbon budgets, and adaptation plans; it created the Climate Change Commission to guide and monitor NZ's climate action.	Promotes sustainable land use and emission reduction practices, which will indirectly influence all landowners, including LB owners.
		National Policy Statements (under RMA)	
National Policy Statement for Freshwater Management (NPS-FM) [70]	2020/Amended 2024	Sets national direction for freshwater protection and use, prioritizing ecosystem health and Te Mana o te Wai.	Influences land use rules affecting LBs; larger (over 5–20 ha) or intensive LBs may be required to manage freshwater risks through local regional plans.

Table 5. *Cont.*

Policy/Act	Year	Scope	Relevance to Lifestyle Blocks
National Policy Statement for Highly Productive Land (NPS-HPL) [68]	2022/Amended 2024	Protects NZ's HPL for long-term land-based primary production. Restricts subdivision, rural lifestyle zoning, and non-agricultural land use.	Restricts LB subdivision and rezoning on HPL, only allowed in limited cases (Clause 3.10). Shapes local planning rules affecting LB development.
		Regional and Planning Tools	
Auckland Unitary Plan (AUP) [29]	2013/Updated 2025	Integrates regional and district planning under the RMA to manage Auckland's land use, growth, and infrastructure over 30 years. Establishes the Rural Urban Boundary (RUB) and zoning rules for development.	Allows LBs in designated zones (e.g., Countryside Living) to manage land fragmentation and rural character, restricts subdivision, land use intensity, and infrastructure provision.
Regional Policy Statements (RPSs)	Ongoing (prepared by regional councils under the RMA)	Set out the overarching resource management goals and directions for each region. Guides regional and district plans.	Influences how LBs are zoned, subdivided, and managed within each region. Some regions (e.g., Waikato, Auckland) explicitly state in their RPSs the need to control lifestyle subdivision due to the pressure it places on land productivity and infrastructure.
Farm Environment Plans (FEPs) [69]	2000s—Ongoing	Assists landowners identify and manage on-farm environmental risks to improve soil, water, and ecosystem outcomes.	Demonstrating good environmental stewardship. In regions (e.g., Canterbury), FEPs are mandatory for properties exceeding certain thresholds (over 20 ha). Larger or intensively managed LBs may fall within scope.
Freshwater Farm Plans (FW-FPs) [54]	2023/ Paused 2024	To identify, assess, and manage on-farm environmental risks to freshwater resources, aligning with the principles of Te Mana o te Wai.	LBs exceeding 20 ha in arable or pastoral use, or 5 ha in horticultural use, are required to develop FW-FPs. Smaller LBs may benefit from voluntary adoption to enhance environmental stewardship.

4.3. Lifestyle Blocks in a Global Context

In Australia, Luck et al. [37] describe the rise of the "tree change" phenomenon, a demographic urban to non-coastal rural movement trend driven by desires for environmental amenities, affordable rural living, and a more nature-oriented lifestyle. This is closely associated with the development of LBs in NZ [7], where similar motivations prioritise amenity and ecological value over commercial agriculture [22,72,74,75]. While such relocation can bring new energy to rural areas, it also introduces challenges that might lead to landscape fragmentation, water quality degradation, and biodiversity loss through low-density housing in sensitive environments [37]. Tensions may also arise between long-term residents and newcomers due to differing expectations, values, and land use practices [37]. Millar and Roots [31] identify policy gaps that permit farmland conversion without addressing long-term food security, calling for land use strategies that incorporate lifestyle landowners into national climate adaptation efforts, which also align with recent policy directions emerging in NZ. Wadduwage [33] further links farm subdivision in peri-urban areas to urban expansion and rising land values. Many former commercial farms are being sold to lifestyle-oriented landowners who may not actively engage in food production activities, resulting in the loss of productive land and raising concerns about Australia's long-term food security.

To address these challenges, Australia has implemented several initiatives to support private landowners in sustainable land stewardship. The state-run Land for Wildlife program supports landowners in conserving wildlife habitats through voluntary ecological assessments and ongoing support such as workshops, field observations, and peer networks [76]. Participants are encouraged to integrate conservation with agricultural or tourism activities, contributing to broader regional biodiversity goals across diverse ecosystems, including forests, wetlands, and other rural landscapes. Additional mechanisms,

such as Conservation Covenants and tax incentives administered through organisations like Trust for Nature, also aim to promote long-term conservation on private land.

In European countries such as the UK, agricultural and rural development policies have traditionally focused on conventional commercial farming, offering limited support for lifestyle-oriented smallholdings. Similarly, Zasada [40] notes that the Common Agricultural Policy (CAP) and its Rural Development Programs (RDPs) often exclude peri-urban farms due to restrictions on land size and tenure. Smallholders often engage in activities shaped by ethical, ecological, and self-sufficiency values, which complicate conventional classifications and governance frameworks [77]. A notable feature of UK smallholdings is their engagement in animal husbandry and biosecurity. Holloway [78] suggests developing an "ethical identity" agricultural support system and employing relational, context-specific practices rooted in care and local knowledge to contribute to more resilient and sustainable farming systems.

Both Zasada [40] and Sutherland et al. [57] suggest that more adaptive policy approaches are needed, including regionally targeted agricultural and rural development schemes specifically adapted to peri-urban conditions, and spatial planning tools such as Green Belts (UK), SCoT (France), and the Finger Plan (Denmark), to indirectly support multifunctional land use and protect semi-agricultural and semi-residential use at the urban fringe.

In the U.S., hobby farms (LBs) have a long history dating back to the Homestead Act of 1862 and continue to balance lifestyle aspirations with agricultural productivity in rural areas [13]. Their function has evolved with industrialisation and urban sprawl. Ninety-one percent of U.S. farms are small, produce only 23% of total output, and rely heavily on off-farm external income [79]. Concentrated in peri-urban areas, the growth of hobby farms in the USA also leads to land fragmentation, rising property prices, and limiting commercial farm expansion. In Oregon's Willamette Valley, small farms grew by 42.3% between 1978 and 1982, with farmland prices rising from USD 1700 to over USD 2600 per acre [20]. Layton [19], drawing on previous studies, links this trend to land subdivisions and changing ownership patterns, which may reduce long-term agricultural productivity. Environmental concerns such as runoff, water nutrient pollution, and erosion are also associated with those small farms.

The U.S. support for hobby and small-scale farms is evident in flexible zoning policies and tax incentives designed to encourage land ownership and retention [13]. The U.S. Department of Agriculture (USDA) also provides financial assistance, such as Farm Ownership and Operating Loans, as well as conservation programs like the Environmental Quality Incentives Program (EQIP) and the Conservation Stewardship Program (CSP), which promote practices that enhance productivity while protecting natural resources. Small farms collectively manage over half of U.S. farmland and account for 82% of land enrolled in conservation initiatives such as the Conservation Reserve Program (CRP) and Wetlands Reserve Program (WRP) [79]. As urbanisation has intensified, farmland preservation policies have played a role in slowing sprawl. However, their success requires effective monitoring to ensure that hobby farming does not compromise agricultural productivity [20]. In this context, sustainable land management and well-targeted incentives remain critical to supporting small farms and integrating them into resilient food systems.

NZ's LBs share similar driving factors and challenges to those of Australia and the U.S., particularly in land fragmentation and biodiversity loss. However, NZ lacks tailored LB-specific policies and initiatives. While instruments like the Farm Environment Plans [69] and QEII National Trust support [80] land stewardship and biodiversity protection, they often rely on covenants with participation thresholds. In contrast, Australia's Land for Wildlife program provides a more inclusive, flexible, and voluntary way of engaging

private landowner communities and knowledge sharing, which could better attract LB owners. Meanwhile, the U.S. financial incentives and targeted conservation schemes also serve as valuable references. Notably, unlike other countries, NZ LBs have occupied a large proportion of its HPL; therefore, international experience can be a good reference, but it is still necessary to address more context-specific solutions that are more NZ-grounded.

5. Discussion

This review has summarised insights from the existing literature on resource use patterns, land management practices, food production, and biodiversity conservation of LBs. While the positive and negative environmental influences have been identified, the overall sustainability levels of LBs are still unknown.

Studies in NZ and Australia have consistently shown that while LB owners often demonstrate strong environmental awareness, this does not always translate into practical, sustainable land management. Barriers include limited knowledge, time, financial resources, physical ability, and a lack of tailored policy support, resulting in minimal engagement in resource management activities and programs [7,10,36,62,72,74,81]. To bridge the gap between awareness and action, broader engagement must be supported by enabling institutional conditions. Lawrence and McManus [51] argue that awareness raising and environmental education alone are not enough to drive systemic change. They emphasise the need for structural interventions, including technical guidance, financial mechanisms, and regulatory planning tools such as subsidies for wastewater management, rainwater harvesting systems, and wetland protection policies. Standard financial incentives are also inadequate; instead, due to the heterogeneity of LBs, more effective approaches include customised education, tailored policy support, and collaboration between policymakers, practitioners, and small-scale landowners [7,36,62,81]. Furthermore, environmental stewardship schemes such as QEII National Trust in NZ and Australia's Land for Wildlife program can help connect private landowners with conservation goals. These initiatives enhance local habitats and support ecosystem services, such as water purification, flood regulation, and food production for urban and rural communities [7,22,43].

LBs can support diverse, small-scale food production through edible gardens, orchards, and livestock keeping, which contributes to self-sufficiency, local food supply, and reduced GHG emissions associated with long-distance food transport [15]. They should therefore be viewed as having a diverse set of land uses with variable implications that at least partly depend on the owners' practices and priorities. However, there is currently no systematic framework to differentiate the diverse environmental performances of LBs. Cook and Fairweather [10] found that around 40% of respondents across lifestyle and part- and full-time farming categories identified their primary land use as LBs, suggesting limited differentiation between LBs and farming categories. They argue that this reflects shortcomings in current classification methods rather than true homogeneity and call for more refined frameworks that better capture smallholders' production activities and income sources. Given LBs' high variability, future research should move beyond broad typologies and develop more nuanced classifications based on factors like block size, land use intensity, owner motivations, and management strategies, to support more accurate sustainability assessments across diverse LB contexts.

To support interlinked priorities of lifestyle amenity, productivity, and sustainability, studies should assess key factors such as water consumption, food production and livestock grazing, energy use and carbon emissions, and biodiversity conservation, as well as identify how different land management approaches shape ecological outcomes and long-term land viability [43,50,51]. In parallel, research should explore how different management methods among LB owners influence ecosystem services, such as soil health, water regula-

tion, pest control, and habitat connectivity. This requires investigating how different land management practices, such as diversified cropping, mixed livestock–forestry systems, ecological restoration, or small-scale agroecology, can optimise the use of HPL while maintaining lifestyle aspirations. Key areas of inquiry include identifying which combinations of land use activities (such as edible gardening, riparian planting, rotational grazing, and biodiversity corridors) most effectively balance environmental sustainability, land productivity, and lifestyle amenity values. This will require assessment of the trade-offs between intensification and sustainability on different block sizes and developing typologies of LB management strategies linked to measurable ecological, productive, and lifestyle outcomes. This can be supported through the development of operational models of LBs that address these potentially competing priorities, while also accounting for biophysical land capacities and local planning frameworks.

International experiences also reveal that, alongside regulatory restrictions, effective sustainability strategies for LBs include voluntary conservation programs, incentive-based programs, technical and advisory support, and stronger community engagement mechanisms. Initiatives such as Australia's Land for Wildlife and the U.S. farm conservation demonstrate the importance of supporting small landholders through flexible, incentive-based approaches. Compared to these models, NZ's current framework remains predominantly regulatory, with emerging but still limited voluntary and incentive-based structures. To strengthen the contribution of LBs to biodiversity conservation and climate resilience, future efforts should focus on integrating them into broader environmental strategies through stewardship programs, tailored incentives, and regional ecological networks.

Complementing program-level initiatives, broader institutional integration of LBs into national environmental governance remains limited. For example, Sise [58] highlights the need to account for LB-related emissions in national GHG emission inventories. Polyakov et al. [22] and Francis [82] both note that traditional natural resource management programs often exclude lifestyle landholders, focusing instead on commercial farmers. To address this gap, planning interventions should explicitly incorporate LBs into sustainable development strategies for peri-urban areas and land management frameworks. Understanding how LBs fit into broader land use planning and climate adaptation policies is crucial for comprehensive environmental governance. Additionally, exploring models of commercial cooperation among LB owners—as community clusters or cooperative networks—could help optimise the use of HPL while balancing environmental and economic sustainability objectives. While these strategies provide useful direction at a conceptual and policy level, their success will ultimately depend on effective implementation. Therefore, more comprehensive case studies, targeted guidance, and technical support are needed to bridge the gap between environmental awareness and sustained, practical action.

In terms of resource consumption and management, although research on water management and biodiversity conservation among LBs has increased, there is still a lack of detailed studies on energy use and transportation patterns. Given that energy consumption and mobility behaviours on LBs differ significantly from urban households due to larger property sizes, off-grid energy reliance, and greater car dependence, future studies should prioritise investigating energy flows, hotspots of consumption, and opportunities for improving efficiency and reducing emissions. Understanding these dynamics is essential for building a comprehensive picture of the environmental implications of LBs.

6. Conclusions

LBs offer both challenges and opportunities for environmental sustainability in peri-urban New Zealand. While their expansion contributes to land fragmentation, resource

consumption, biodiversity loss, and greenhouse gas emissions, many LB owners demonstrate strong environmental awareness and adopt sustainable land use practices such as agroforestry, permaculture, and renewable energy systems. Their non-commercial motivations allow diverse, regenerative land management approaches that can enhance ecosystem services and reduce environmental impacts. However, inefficient land management and other environmental impacts related to small-scale farming and recreational activities require greater attention. Furthermore, integrating management of LBs into environmental policy frameworks—through targeted incentives, carbon credit programs, and cooperative sustainability initiatives—could help to align LB owners' lifestyle aspirations with regional and national environmental and food security goals. Future research should therefore investigate how this can be achieved through (a) supporting LB owners to change their practices to enhance environmental outcomes, and (b) integrating management of LBs into regional and national environmental policy.

Limitations and Future Research

The systematic review used Google Scholar and Scopus databases, and other databases, such as Web of Science, were not included. The keyword selection was primarily environment-focused and did not fully incorporate the broader social or economic viewpoint of LBs. This review mainly focuses on LBs in NZ and a few other high-income countries (e.g., Australia, the US, Canada, the UK) and does not include insights from emerging economies. However, countries like China, Japan, and India are also experiencing rapid peri-urban change and the rise of non-commercial or mixed land uses similar to LBs. While these contexts differ, they offer valuable perspectives on land fragmentation, food security, and rural–urban land governance. Future research should broaden its geographic scope to include these diverse cases and explore both local and transferable strategies for sustainable land management.

To better understand the overall sustainability of LBs, more detailed data on resource flows and both on-block and off-block activities and practices need to be collected to identify key environmental hotspots and develop more targeted assessment strategies for LB management. While improving the sustainability level, future research and planning policies should also focus on maintaining land productivity and supporting lifestyle amenity values of already subdivided land, particularly existing LBs. Additionally, attention should be paid to recent changes affecting LBs, particularly following the COVID-19 pandemic and the publication of the NPS-HPL in 2022. The pandemic restrictions and increased remote work opportunities may have intensified interest in rural living [7], as individuals spend less time commuting and seek lifestyles that support teleworking, potentially increasing the demand for LBs. In contrast, the NPS-HPL has introduced stricter controls on land subdivision to protect NZ's HPL, which may constrain LB development. These contrasting influences have not yet been systematically analysed and underscore the importance of investigating the long-term environmental, social, economic, and policy implications of LBs.

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Appendix A

This appendix presents the final list of sources included in the systematic review (Table A1), following the screening and selection process described in the methodology. It includes academic publications as well as New Zealand government reports and policy documents. Each source is categorized by author, year, country, and key thematic focus to illustrate the breadth of literature informing this study.

Table A1. Summary of included academic and policy documents in the systematic review.

Author	Year	Country	Key Themes
		Academic Publications	
Layton [19]	1980	Canada	Hobby farm; Rural–urban fringe Land fragmentation
Meister & Stewart [83]	1980	New Zealand	Smallholdings; Taranaki
Daniels [13]	1986	United States	Hobby farming; Rural development Commercial agriculture
Daniels & Nelson [20]	1986	United States	Hobby farms; Oregon Farmland preservation program exclusive farm use (EFU) zones
Fairweather [8]	1993	New Zealand	Smallholdings Lifestyle farming; Owner motivation
Swaffield & Fairweather [34]	1998	New Zealand	Rural subdivision; Smallholder Christchurch
Hamilton [84]	1999	New Zealand	Lifestyle blocks Dunedin
Lee [35]	1999	New Zealand	Rural subdivision; Lifestyle block Selwyn District; Farmer
Fairweather & Robertson [7]	2000	New Zealand	Smallholdings; Canterbury Land use; Motivation
Holloway [77]	2002	United Kingdom	Smallholding; Hobby farming Commercial farming
Sanson et al. [9]	2004	New Zealand	Smallholdings Lifestyle blocks
Lillis et al. [16]	2005	New Zealand	Smallholdings Agricultural production; Land use
Cook & Fairweather [85]	2005	New Zealand	Smallholding; Lifestyle block Land use change; Subdivision Selwyn District
Cook & Fairweather [10]	2005	New Zealand	Smallholdings; Lifestyle blocks Rural land use; Environmental impact
Francis [82]	2006	Australia	Small lifestyle properties Natural resource management
Wright [86]	2006	New Zealand	Peri-urban; Subdivision Land use change; Matangi
Kerr & Sharp [41]	2007	New Zealand	Community land care; Local capacity; Environmental governance; Peri-urban; Rural land use
Hollier & Reid [87]	2007	Australia	Sustainable Land Management Small lifestyle farm
Cadieux [88]	2008	New Zealand	Exurban; Lifestyle Urban planning; Christchurch

Table A1. *Cont.*

Author	Year	Country	Key Themes
Stobbe et al. [89]	2008	Canada	Hobby farmers; Agricultural land Reserve Urban–rural fringe; Farmland fragmentation
Lawrence & McManus [51]	2008	Australia	Sustainable lifestyle program Household water consumption
Pannell & Wilkinson [36]	2009	Australia	Smallholders; Conservation Environmental management; Land use
Lynn et al. [23]	2009	New Zealand	Land Use Capability (LUC); Soil erosion; Sustainable land use; Land management
McAloon [38]	2009	New Zealand	Land ownership; Lifestyle blocks; Larger farms; Land aggregation
Hoppe et al. [79]	2010	United States	Small farm; Off-farm income Agricultural policy
Gill et al. [74]	2010	Australia	Hobby farming; Amenity migration Natural resource management Ecosystem fragmentation
Duncan et al. [90]	2010	Australia	Landscape history; Land use change native vegetation
Argent et al. [32]	2010	Australia	Rural amenity Counter urbanisation
Luck et al. [37]	2010	Australia	Demographic change; Rural landscapes Tree change/sea change; Environmental impact; Land use planning
Millar & Roots [31]	2012	Australia	Food production; Food security Land use planning; Rural communities
De Rijke [75]	2012	Australia	Peri-urban; Community identity Environmental dispute; Queensland
Moller & Moller [45]	2012	New Zealand	Lifestyle values; Tūmai Beach Sanctuary; Ecosystems
Sutherland et al. [21]	2012	United Kingdom	Lifestyle land management Hobby farming; Scotland Amenity migration
Morrison et al. [72]	2012	Australia	Natural resource management Hobby farmer; Environmental conservation Market-based instrument; Lifestyle
Andrew & Dymond [5]	2013	New Zealand	Lifestyle block; High-class land
Meurk et al. [4]	2013	New Zealand	Ecosystem services Peri-urban; Biodiversity
Polyakov et al. [22]	2013	Australia	Lifestyle landowners Ecosystem services; Native vegetation
Hart et al. [44]	2014	New Zealand	Land fragmentation Rural subdivision; High-capability land Regional policy; Monitoring
Meadows et al. [81]	2014	Australia	Small-scale rural lifestyle landowner Resource management programme Amenity landscape; Incentive programme
Curran-Cournane et al. [42]	2014	New Zealand	High-class land Ecosystem services; Auckland

Table A1. *Cont.*

Author	Year	Country	Key Themes
Gooderham et al. [91]	2014	New Zealand	Rural urban relationship Land use change Auckland, Waikato region
Davis et al. [3]	2015	Australia	Freshwater ecosystems Land use intensification
Marshall et al. [65]	2016	Australia	Community-based Natural resource management Invasive pests; Biosecurity
Curran-Cournane et al. [6]	2016	New Zealand	Rural fragmentation; Policy response Rural farming values; Auckland
Silva [30]	2018	New Zealand	Urban sprawl; Pukekohe Auckland; Agricultural land; Land use change
Sutherland et al. [57]	2019	United Kingdom	Smallholding; Non-commercial farming Estates; Hobby farming; Scotland
Eade [15]	2019	New Zealand	Lifestyle blocks Productive land; Pukekohe
Rivera et al. [92]	2019	Worldwide	Small farm; Sustainability; Food systems
Holloway [78]	2019	United Kingdom	Smallholdings; Livestock; Biosecurity; Animal welfare
Sambell et al. [66]	2019	Australia	Landscape change Biodiversity; Land management
Carrick et al. [56]	2020	New Zealand	Land fragmentation Highly productive land (HPL) Land use capability (LUC)
Adeyeye et al. [52]	2020	United Kingdom	Water marginality; Peri-urban Lifestyle-driven water demand
Sutherland [93]	2020	United Kingdom	Hobby farmer; Lifestyle; Scotland Amenity Agriculture; Parish Study
Pearson [7]	2021	New Zealand	Lifestyle properties; Ecosystem service Biodiversity; Peri-urban, Palmerston North
Wadduwage [33]	2021	Australia	Peri-urban farmer Land use decision; Adelaide
Stats NZ [2]	2021	New Zealand	Land fragmentation; Urban expansion Highly productive land (HPL)
Sise [58]	2022	New Zealand	Lifestyle block; Small-scale farming Livestock; GHG emission
Song et al. [43]	2022	Australia	Hobby farm; Part-time farmer Lifestyle; rural–urban fringe; Adelaide Hill
Davis et al. [3]	2023	New Zealand	Peri-urban; Landscape House; Food production
Robinson & Song [55]	2023	Australia	Environmental watering Horticulture; River land
Curran-Cournane et al. [94]	2023	New Zealand	Land fragmentation; National policy Urban expansion; Versatile land
Qi [59]	2023	New Zealand	Lifestyle block; Solar power Water pumping; Irrigation
Real Estate Institute of New Zealand (REINZ) [95]	2024	New Zealand	Subdivision; Productive land Lifestyle properties

Table A1. *Cont.*

Author	Year	Country	Key Themes
Polyakov et al. [62]	2024	New Zealand	Native afforestation Rural landholder; Policy tools
Villamor et al. [47]	2025	New Zealand	Water; Tree; Farmers; Lifestyle
New Zealand Government Report and National and Regional Policy			
New Zealand Government [67]	1991–2024	Resource Management Act 1991	Sustainable management Integrated resource management
Environment Canterbury [69]	2000s—ongoing	Farm Environment Plans (FEPs)	Zone-specific requirements; Environmental risks and mitigations; Good management practices; Mahinga Kai
Auckland Council [29]	2013–2025	Auckland Unitary Plan	Rural–urban boundary (RUB)
Our Land and Water National Science Challenge (OLW) [46]	2018	Our Land and Water Strategy 2019–2024	Land fragmentation Urban expansion; Versatile land National policy
Bay of Plenty Regional Council Toi Moana [50]	2018	Your lifestyle block and Lake Rotorua	Lifestyle block water quality; Lake Rotorua land use practices
MPI [18]	2018	MPI study of New Zealand lifestyle blocks and animal welfare	Lifestyle blocks Animal welfare
MfE & Stats NZ [26]	2019	Environment Aotearoa 2019	Urban expansion; Land fragmentation Highly productive land; Habitat loss
MfE, & MPI [24]	2019	Valuing highly productive land	Highly productive land
MfE, & Stats NZ [1]	2021	Our Land 2021	Land fragmentation; Lifestyle blocks Highly productive land; Urban expansion Agricultural intensification
MfE [68]	2022–2024	National Policy Statement for Highly Productive Land (NPS-HPL)	Highly Productive Land Peri-urban; Land fragmentation Planning policy; Land use capability (LUC); Urban rezoning; Subdivision Control
MfE [70]	2020–2024	National Policy Statement for Freshwater Management (NPS-FM)	Te Mana o te Wai Freshwater management; Ecosystem health; Water quality
MfE & Stats NZ [27]	2024	Our Land 2024	Environmental reporting; Climate change Land use and management Ecosystem services; Biodiversity conservation; Land fragmentation
MPI [54]	2020–2024 Pause	Freshwater Farm Plan	Freshwater environment; Risk assessment; Farm mapping; Good management practices

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Analysis of the Correlation Between the Accessibility of Built Environment Elements and Residents' Self-Rated Health in New Rural Communities

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Abstract: In the contexts of rapid urbanization and the Healthy China Strategy, understanding how the built environment affects residents' health has become a pressing issue for the development of new rural communities. This study aims to investigate the associations between facility accessibility and residents' health, and to provide evidence for health-oriented rural planning. Taking Pujiang County in Chengdu as the case study, we measured the accessibility of nine categories of facilities using GIS-based network analysis and evaluated residents' health through the Self-Rated Health Measurement Scale (SRHMS). Gradient Boosting Decision Trees (GBDT) combined with SHAP interpretation were employed to examine and explain the influence of accessibility factors on health outcomes. The results indicate that the accessibility of road entrances, public toilets, garbage transfer points, schools, and community service centers is negatively associated with residents' health, with variations across physical, mental, and social health dimensions. Moreover, social health is insufficiently explained by physical accessibility alone, implying the additional importance of social and cultural conditions. These findings offer practical guidance for optimizing facility layout and spatial design in new rural communities and provide an empirical basis for promoting health-oriented rural planning in China and similar contexts.

Keywords: built environment; new rural communities; self-rated health; optimization strategy

1. Introduction

In recent years, China's urbanization has entered a stage of high-quality development, in which the construction of new rural communities is regarded as a crucial mechanism for promoting urban–rural integration, improving living environments, and enhancing public services [1–4]. New rural communities refer to modern and centralized residential settlements formed within designated rural areas through standardized planning, unified construction, and the integration of social organization [2,5]. Compared with traditional scattered rural settlements, this model alleviates problems such as resource wastage, inadequate public facilities, and insufficient health services by concentrating layouts, standardizing infrastructure planning, and improving the provision of public service facilities [6,7]. However, despite significant improvements in hardware conditions, the maintenance and enhancement of residents' health outcomes have not met expectations, prompting further academic exploration into the factors related to the built environment. The built environment refers to the physical space created and transformed by human activities, including road networks, public service facilities, green spaces, and open spaces [8]. Among various built environment features, accessibility is considered a key mechanistic

variable linking spatial layout and resident health, reflecting the ease with which residents can obtain specific resources or services within certain time and cost constraints [9–11]. In new rural communities, although spatial layouts are centralized and functional zoning is clearly defined, resource distribution may still exhibit structural imbalances. The level of accessibility directly affects opportunities for residents to engage in physical exercise, access medical services, and participate in public activities and social interactions, thereby influencing their health outcomes [12,13]. Therefore, examining the relationship between the built environment of new rural communities and resident health from an "accessibility" perspective not only contributes to deepening academic research on urban and rural healthy spaces but also addresses the practical need to optimize the allocation of public resources and improve the health levels of rural residents.

A substantial body of empirical evidence demonstrates that the accessibility of the built environment is significantly associated with residents' self-rated health, with marked disparities observed across urban–rural contexts and different social groups [8,14–16]. Comparative studies in China indicate that rural residents are generally disadvantaged in terms of access to public facilities, transportation nodes, and recreational spaces, which may partly explain their lower health outcomes compared to urban residents [17]. Similar patterns were confirmed in Europe through four waves of Eurobarometer cross-sectional surveys [18]. The health effects of accessibility to different types of facilities exhibit considerable heterogeneity and complexity [19–21]. Green space accessibility is positively linked to mental well-being, physical activity, and cardiovascular health, although these effects vary by gender, age, and socioeconomic status [22,23]. A longitudinal study in Wales demonstrated that residential proximity to green and blue space was associated with long-term improvements in mental health, particularly among socioeconomically disadvantaged groups [24]. Proximity to sports and recreational facilities generally promotes physical activity, however its effectiveness depends on facility quality, safety, and sociocultural context [25]. Evidence from Sweden indicates that these positive effects are substantially weaker in low socioeconomic status (SES) neighborhoods compared to high-SES communities [26]. Public transportation accessibility may also improve health by encouraging walking and social interaction [27–29]. However, the finding from suburban Scarborough, Canada, suggests that low-income populations may experience adverse effects due to increased exposure to environmental risks near transit nodes [30]. In terms of measurement approaches, researchers have employed diverse methods to assess accessibility, ranging from simple Euclidean distances to network-based measures that more accurately reflect actual travel conditions, and further to complex models incorporating travel cost and service capacity [31–33]. A systematic review of health service accessibility in Australia over the past two decades highlighted that network-based measures are particularly critical in addressing inequalities between urban and remote rural areas [34]. Regarding health measurement, self-rated health (SRH) has been widely used by the World Health Organization, the U.S. Centers for Disease Control and Prevention, and the European Union for population health monitoring. Its reliability and validity have been consistently validated in large-scale surveys [35–37]. Some scholars have further differentiated within the SRH framework among physical, mental, and social dimensions to reveal the multi-level characteristics of health [38,39].

Although existing studies have yielded substantial findings, research focusing on new rural communities remains inadequate. First, there is a lack of targeted investigation into the specific research object [40,41]. Most studies concentrate on urban residents or urban–rural comparisons, with limited systematic analysis devoted to new rural communities as an emerging spatial form [5,42]. These communities differ from both traditional villages and urban neighborhoods in terms of spatial intensification, functional zoning, and transportation organization, suggesting that the mechanisms through which accessibility affects health may be unique. Second, existing research often focuses on a single type of facility (such as healthcare or green spaces), paying insufficient attention to the combined effects of multiple facility types [43]. Although a few recent studies have begun to incorporate factors such as public service centers, public toilets, squares, garbage transfer points, and educational resources, overall, this line of inquiry remains underdeveloped [44–47]. Third, methodological limitations are notable. Traditional statistical methods, such as multiple regression and spatial regression, can reveal linear relationships but often fail to capture complex nonlinear effects and interactions between variables [48]. In recent years, machine learning methods, such as gradient boosting machines and random forests, have been increasingly applied in public health and built environment research [49]. However, their use remains relatively limited in studies on the relationship between accessibility and health, particularly those incorporating interpretability approaches, such as SHAP, to uncover the marginal effects of different types of facilities.

Building upon the identified research gaps, this study examines the relationship between the built environment and residents' health in new rural communities in China from an accessibility perspective. To this end, we constructed a multidimensional accessibility indicator system covering public services, daily amenities, and recreational environments, and employed GIS-based measurement methods to obtain precise spatial data. Meanwhile, self-rated health (SRH) was used as the core health measurement tool to comprehensively evaluate residents' physical, mental, and social well-being. Methodologically, the Gradient Boosted Decision Trees (GBDT) model along with the SHAP interpretability approach were introduced to uncover the nonlinear effects and marginal contributions of various built environment elements on health. Through this framework, this study not only addresses the limitations of traditional statistical methods in capturing complex relationships but also provides new evidence for understanding the interaction mechanisms between spatial characteristics and health outcomes in new rural communities.

To achieve the aforementioned research objectives, the structure of this paper is organized as follows: Section 2 introduces the materials and methods, including the measurement of self-rated health and the accessibility of built environment elements, the modeling approach using Gradient Boosting Decision Trees (GBDT), and the interpretability analysis supplemented by SHAP. Section 3 presents the model results, highlighting the strength and variation in associations between the accessibility of different built environment elements and residents' self-rated health. Section 4 discusses the underlying mechanisms behind the findings and derives policy implications along with future research directions based on the results. Section 5 summarizes the main findings, discusses the theoretical and practical significance of the results, and reflects on the study's limitations and future directions. Through rigorous data analysis and methodological innovation, this study aims to provide new evidence and theoretical insights for health-oriented planning and management of new rural communities.

2. Materials and Methods

2.1. Study Area

The survey area of this study is Pujiang County, Chengdu City, Sichuan Province, covering six new rural communities (Figure 1). All these communities belong to the same county and were constructed in accordance with the unified planning of Chengdu's new rural construction, showing a high degree of consistency in terms of spatial layout, public facility allocation, and residential form. Most residents are relocated and resettled as a whole, with relatively similar population structure and social and cultural backgrounds; the main groups are generally middle-aged and elderly farmers and migrant workers returning to their hometowns, and the forms of community activities are quite similar. Spatially, the distance between the communities is relatively short, with the maximum distance between any two points not exceeding 20 km. This similarity in the built environment and population-social conditions provides a favorable prerequisite for cross-community data collection and model analysis.

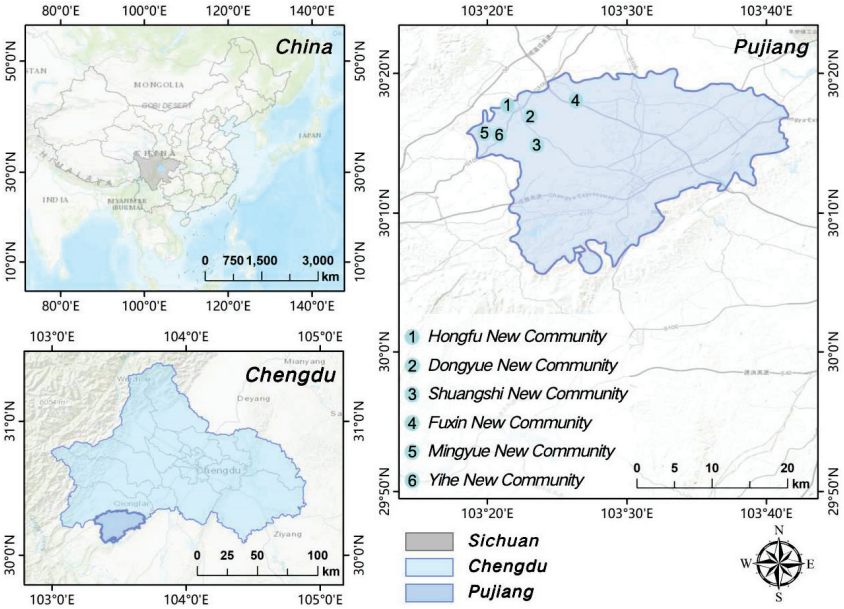


Figure 1. Map of the study area.

The survey was conducted in July 2023 by eight trained researchers. Data collection methods included household questionnaires (the questionnaire is provided in Appendix A), on-site guided surveys, and semi-structured interviews. To facilitate statistical modeling, demographic variables were numerically coded (Table 1). To minimize comprehension biases due to older age or limited education, the research team, with assistance from local village committees, provided necessary explanations to ensure accurate and complete questionnaire responses. A total of 105 questionnaires were distributed, with 77 valid responses received. In accordance with the Self-Rated Health Measurement Scale (SRHMS) requirement that respondents must be at least 14 years old, ineligible individuals were excluded. After further processing of missing values and outliers, a final valid sample of 72 responses meeting the research criteria was obtained. This sample covers six communities, with balanced age distribution and reasonable gender proportion, reflecting the overall profile of residents in the target area.

Table 1. Coding Scheme of Demographic Characteristics.

Variables	Code	Definition
Gender	1	Male
	2	Female
Age	-	-
Career	1	peasants
	2	government official
	3	individual businesses
	4	workers
Marital status	1	married
	2	unmarried
	3	divorcee
	4	bereaved of one's spouse
Settlement	1	Living in a rural community
	2	Living in a rural community or county
Income	1	<50,000 CNY
	2	50,000 CNY–100,000 CNY
	3	100,000 CNY–200,000 CNY
	4	>200,000 CNY
Cultivation	1	Still engaged in farming activities
	2	Not engaged in farming activities

Missing values were coded as 0.

2.2. Measurement

2.2.1. Accessibility

Researchers initially quantified the elements of the built environment using the "3Ds" framework (density, diversity, design). Subsequently, this framework was gradually expanded into the "5Ds" framework, with the addition of destination accessibility and distance to transit, which has been widely adopted in studies on travel behavior and health effects [28,50,51]. Among the dimensions of this framework, density and diversity are more reflective of the characteristics of the overall spatial pattern, rather than the accessibility dimension at the individual level. Therefore, based on the "5Ds" framework, this study selects the accessibility of three dimensions—design, destination, and transportation—as the accessibility indicator system for this research. Specifically, the design dimension includes green space, square, public toilet, community service center, and garbage transfer point; the destination dimension includes hospital and school; and the transportation dimension includes road entrance and bus stop. This measurement system not only aligns with the theoretical development context of accessibility research in built environment studies but also adapts to the actual construction situation of new rural communities.

In terms of measurement methods, this study employed Geographic Information System (GIS) technology to obtain the spatial distance between residents' addresses and various built environment elements [52,53]. Based on vector maps from the National Platform for Common Geospatial Information Services, combined with facility locations confirmed through field surveys, nine built environment elements were spatially matched with the residential locations of the 72 surveyed samples. Using the Network Analysis tool in ArcMap 10.8, the shortest travel distance from each residence to various facilities was calculated and used as the indicator of accessibility. This approach more accurately reflects actual travel conditions compared to straight-line distance, ensuring the accuracy and comparability of the measurement results.

2.2.2. Self-Rated Health

Residents' health status was assessed using the Self-Rated Health Measurement Scale (SRHMS). Developed by domestic scholars, the scale draws on internationally recognized health measurement tools, such as the Short Form 36 Health Survey (SF-36) and Medical Outcomes Study scales (MOS), has been adapted to the Chinese context with demonstrated reliability and validity in large-scale surveys [54,55]. The SRHMS consists of three subscales: physical health (170 points), mental health (150 points), and social health (120 points), comprising a total of 10 dimensions and 48 items. This multi-item structure allows a comprehensive assessment of health across multiple levels.

During the survey, participants rated each item based on their personal perception using a scale from 0 to 10, with higher scores indicating better self-rated health. With reference to norm-based results provided in previous studies, the SRHMS serves as a robust tool for measuring overall health status and variations across different health dimensions. Owing to its comprehensive structure and cross-cultural comparability, this study adopted the SRHMS as the core health measure for the dependent variable, providing a reliable basis for examining the relationship between built environment accessibility and multidimensional health outcomes.

2.3. Methods

2.3.1. Research Framework

To systematically analyze the relationship between built environment accessibility and self-rated health in new rural communities, this study developed a stepwise analytical framework (Figure 2). First, questionnaire surveys and field investigations were conducted to collect residents' health data and spatial data on the built environment. Second, GIS-based network analysis was used to measure accessibility indicators from residences to various facilities, while the SRHMS was applied to quantify health levels. For the processing of the dependent variable, the SRHMS scores were transformed from continuous variables into categorical variables using three distinct cutoff methods—mean, median, and mid-range—to compare model performance across classification strategies. In terms of statistical analysis, the Gradient Boosted Decision Trees (GBDT) model was introduced to capture nonlinear relationships, supplemented by the SHapley Additive exPlanations (SHAP) method to enhance model interpretability and reveal the marginal contributions of accessibility to different built environment elements. Finally, based on the model results, design and planning recommendations were proposed for health-oriented spatial optimization in new rural communities. This framework not only overcomes limitations of traditional linear approaches but also helps elucidate the mechanisms through which complex environmental factors influence multidimensional health outcomes.

2.3.2. GBDT

This study employs a Gradient Boosting (GB) framework with Decision Trees as base learners, i.e., a Gradient Boosted Decision Trees (GBDT) model. GBDT is an ensemble learning method based on the boosting principle. It sequentially trains multiple weak learners (typically regression trees), where each iteration fits a new weak learner to the residual errors from the previous round, thereby minimizing the value of the loss function [56]. The core idea is to iteratively optimize the following objective:

$$F_m(x) = F_{m-1}(x) + \nu\gamma_m h_m(x) \tag{1}$$

where $F_m(x)$ denotes the model at the m-th iteration, $h_m(x)$ is the regression tree fitted to the residual errors; γ_m represents the optimal step size, and ν is the learning rate.

The residuals are given by the negative gradient:

$$r_{im} = -\left[\frac{\partial L(y_i, F(x_i))}{\partial F(x_i)}\right]_{F=F_{m-1}} \quad (2)$$

where r_{im} denotes the residual of sample i at the m-th iteration, $L(y_i, F(x_i))$ is the loss function that quantifies the discrepancy between the predicted and true values, $F(x_i)$ represents the predicted value of sample i, and F_{m-1} refers to the model obtained from the $(m-1)$-th iteration.

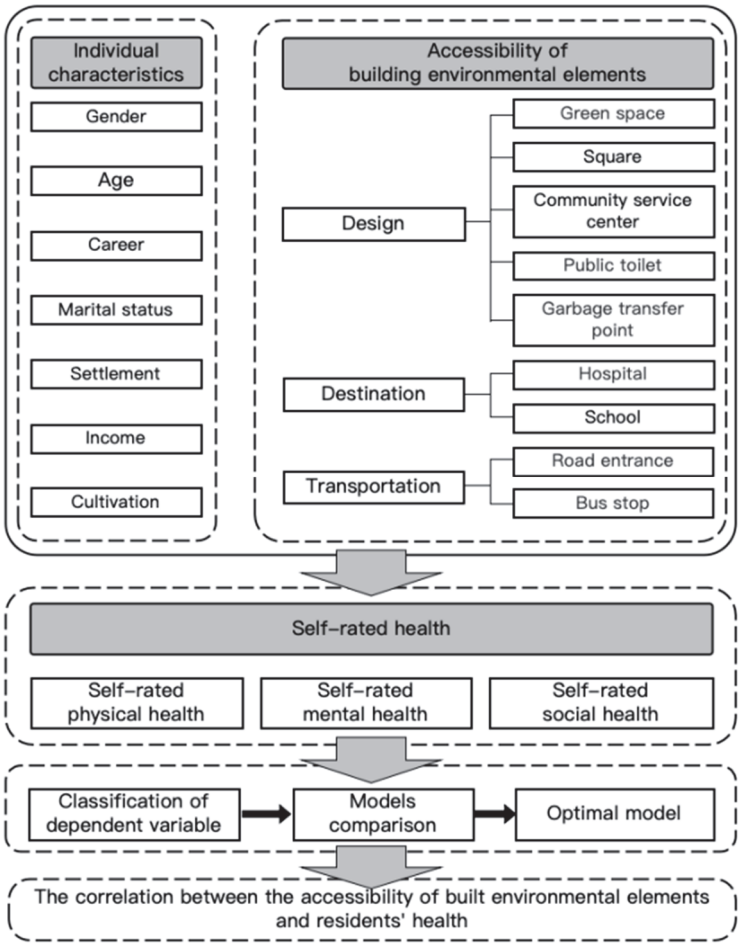


Figure 2. Path of research on the correlation between the accessibility of built environment elements and residents' self-rated health in new rural communities.

The GBDT model effectively captures complex nonlinear relationships and handles high-dimensional feature data, with relatively flexible requirements regarding variable distribution and scale. It can simultaneously process both numerical and categorical features, offering strong applicability. The model also demonstrates excellent generalization performance. By tuning hyperparameters such as the learning rate, base learner depth, and number of iterations, it achieves a balance between bias and variance, thereby improving prediction stability. In studying health issues in new rural communities, nonlinear associations and interaction effects often exist between the built environment and health outcomes. The GBDT model is capable of capturing such complex relationships more comprehensively, making it particularly suitable for research contexts with limited sample sizes but numerous features. In this study, the GBDT model was implemented using the Scikit-learn library (version 1.2.2, Python 3.10). Key hyperparameters were optimized

through five-fold cross-validation and grid search, with the Area Under the Curve (AUC) used as the evaluation metric to ensure model robustness and predictive accuracy.

2.3.3. SHAP

While the GBDT model demonstrates significant advantages in predictive accuracy, its "black box" nature limits intuitive understanding of causal mechanisms. To enhance the interpretability of the model, this study introduces SHAP (SHapley Additive exPlanations), a method rooted in cooperative game theory that leverages Shapley values. By quantifying the marginal contribution of each feature to the prediction outcome across all possible feature subsets, SHAP assigns importance scores to features and indicates the direction (positive or negative) of their effects. The Shapley value is computed as follows:

$$f(x) = \phi_0 + \sum_{j=1}^{p} \phi_j \tag{3}$$

where ϕ_0 is the mean prediction value across all samples, and ϕ_j denotes the contribution of feature j to the prediction outcome.

The Shapley value is calculated as follows:

$$\Phi_j = \sum_{S \subseteq N \setminus \{j\}} \frac{|S|!(p - |S| - 1)!}{p!} \left[f_{S \cup \{j\}} \left(x_{S \cup \{j\}} \right) - f_S(x_S) \right] \tag{4}$$

where N represents the entire set of features, S denotes a subset of features excluding j, and f_S is the prediction based on feature subset S.

The SHAP method has two major theoretical advantages, namely consistency and local accuracy. It can simultaneously provide both global feature importance rankings and local explanations for individual predictions. In this study, SHAP analysis was conducted using the SHAP package (version 0.41.0, Python 3.10). This method was employed not only to identify the built environment and personal attribute variables that contribute most to predicting residents' self-rated health but also to reveal nonlinear relationships and threshold effects between different features and health outcomes. This approach offered robust data support for result interpretation and the formulation of health-oriented design strategies [57].

3. Results

3.1. Model Comparison

Prior to formal analysis, this study compared the performance of three classification methods for SRHMS health data—mean, median, and mid-range (Tables 2–4). Overall, the classification approaches showed significant differences in model performance. The mid-range classification achieved the highest AUC (0.8846) in the social health dimension, with near-perfect accuracy and recall. However, it performed poorly in both comprehensive health (AUC = 0.5139) and physical health (AUC = 0.3056), indicating limited model stability. The median classification also yielded suboptimal results overall: while the mental health model achieved an acceptable AUC (0.6161), performance in other dimensions was close to random level. In contrast, the mean classification demonstrated the most robust overall performance. It performed notably well in both comprehensive health (AUC = 0.7407) and physical health (AUC = 0.703). Although the mental health model had relatively low recall, its AUC (0.6852) still surpassed those obtained with other methods. Only in the social health dimension did this method show limited explanatory power (AUC = 0.5000), suggesting that built environment accessibility offers little predictive insight for this aspect of health. In summary, the mean classification exhibited clear advantages in predicting

overall and physical health, with relatively balanced performance across dimensions. Therefore, all subsequent results and discussions in this paper are based on the mean classification approach.

Table 2. Comparison of Model Performance under Mid-Range Classification.

	AUC	Accuracy	Precision	Recall	F1-Score
Self-rated Health	0.5139	0.7333	0.7857	0.9167	0.8462
Self-rated Physical Health	0.3056	0.6000	0.7500	0.7500	0.7500
Self-rated Mental Health	0.4318	0.6667	0.7143	0.9091	0.8000
Self-rated Social Health	0.8846	0.9333	0.9286	1.0000	0.9630

Table 3. Comparison of Model Performance under Median-based Classification.

	AUC	Accuracy	Precision	Recall	F1-Score
Self-rated Health	0.5179	0.4667	0.4444	0.5714	0.5000
Self-rated Physical Health	0.3750	0.4000	0.2500	0.1429	0.1818
Self-rated Mental Health	0.6161	0.6667	0.6250	0.7143	0.6667
Self-rated Social Health	0.5893	0.6000	0.5714	0.5714	0.5714

Table 4. Comparison of Model Performance under Mean-based Classification.

	AUC	Accuracy	Precision	Recall	F1-Score
Self-rated Health	0.7407	0.6667	0.7500	0.6667	0.7059
Self-rated Physical Health	0.7037	0.6667	0.7000	0.7778	0.7368
Self-rated Mental Health	0.6852	0.5333	0.7500	0.3333	0.4615
Self-rated Social Health	0.5000	0.6000	0.6154	0.8889	0.7273

3.2. Overall Model Performance Evaluation

Based on the mean-based classification results, this study constructed four GB classification models targeting comprehensive self-rated health, self-rated physical health, self-rated mental health, and self-rated social health, respectively (Table 4). The comprehensive self-rated health model achieved an AUC value of 0.7407, an overall accuracy of 0.6667, precision and recall values of 0.7500 and 0.6667, respectively, and an F1-score of 0.7059, indicating strong discriminative ability and a balanced performance between precision and recall in predicting overall health levels. The self-rated physical health model attained an AUC value of 0.7037 and an accuracy of 0.6667. Its recall (0.7778) was higher than its precision (0.7000), suggesting a relative advantage in identifying individuals with poorer physical health, though with slightly lower precision compared to the comprehensive health model. The self-rated mental health model demonstrated relatively weaker performance, with an AUC value of 0.6852, an accuracy of 0.5333, a precision of 0.7500, but a recall of only 0.3333, resulting in a low F1-score (0.4615). This indicates that while the model effectively identified individuals predicted as healthy, its ability to detect those with poorer mental health was limited. The self-rated social health model yielded an AUC value of only 0.5000, approaching random classification performance. However, its recall reached 0.8889, indicating a tendency to predict most samples as healthy, which consequently reduced its precision (0.6154). The F1-score was 0.7273.

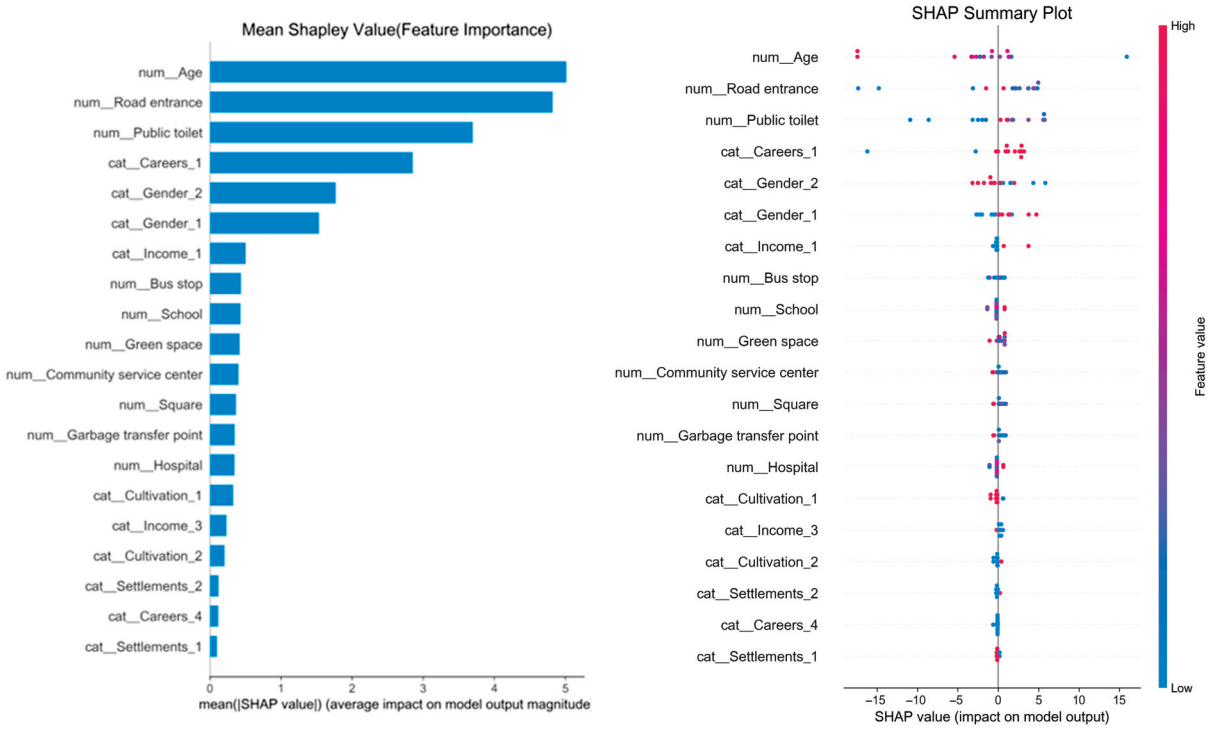
In summary, the comprehensive self-rated health and self-rated physical health models exhibited the best performance in distinguishing different health statuses, followed by the self-rated mental health model. The low AUC value of the social health model suggests that built environment and personal attribute features contributed limited predictive power for this dimension. Therefore, to ensure the reliability of the results, subsequent analyses will focus only on the first three health dimensions—comprehensive health, physical health, and mental health—for SHAP-based feature importance and local interpretation.

3.3. Self-Rated Health

The comprehensive health model demonstrated the best predictive performance (AUC = 0.7407, F1 = 0.7059). The SHAP summary plot revealed that the three most important features were, in descending order: age (num_Age) has the highest mean | SHAP | value (5.01), and its mean SHAP value is significantly negative (−2.32). This indicates that age growth is highly correlated with self-rated health, showing a negative correlation. In the beeswarm plot, older individuals (red dots) were almost entirely distributed in the negative SHAP value region (−5 to 0), while younger individuals (blue dots) were located in the positive region, further confirming this trend. Distance to road entrance ranked second in importance (mean | SHAP | = 4.82). Although its overall mean SHAP value was close to zero, its impact was asymmetrical: most high-distance values showed no significant positive effect, while low-distance samples exhibited clear negative contributions (−10 to −15), suggesting that transportation convenience may come with noise and pollution risks. Distance to public toilet ranked third (mean | SHAP | = 3.70), showing a "closer-negative, farther-positive" pattern: samples closer to public toilet mostly had negative SHAP values, while those farther away showed partial positive contributions. Additionally, individuals identified as farmers (cat_Careers_1) almost entirely fell within the positive region, indicating a tendency toward better self-rated health in this group. The gender variable showed a divergent pattern: most males (cat_Gender_1) were located in the positive region, while females (cat_Gender_2) were concentrated in the negative region. Other environmental factors, such as distance to bus stop, school, and green space, ranked lower but still showed certain marginal contributions (Table 5, Figure 3).

Table 5. SHAP Feature Importance for Self-Rated Health.

Feature Name	Mean | SHAP | Value	Mean SHAP Value	Importance Rank
num__Age	5.01	−2.32	1
num__Road entrance	4.82	−0.07	2
num__Public toilet	3.70	−0.11	3
cat__Careers_1	2.86	0.29	4
cat__Gender_2	1.77	0.40	5
cat__Gender_1	1.53	0.29	6
cat__Income_1	0.50	0.09	7
num__Bus stop	0.44	0.03	8
num__School	0.43	−0.22	9
num__Green space	0.42	0.25	10



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

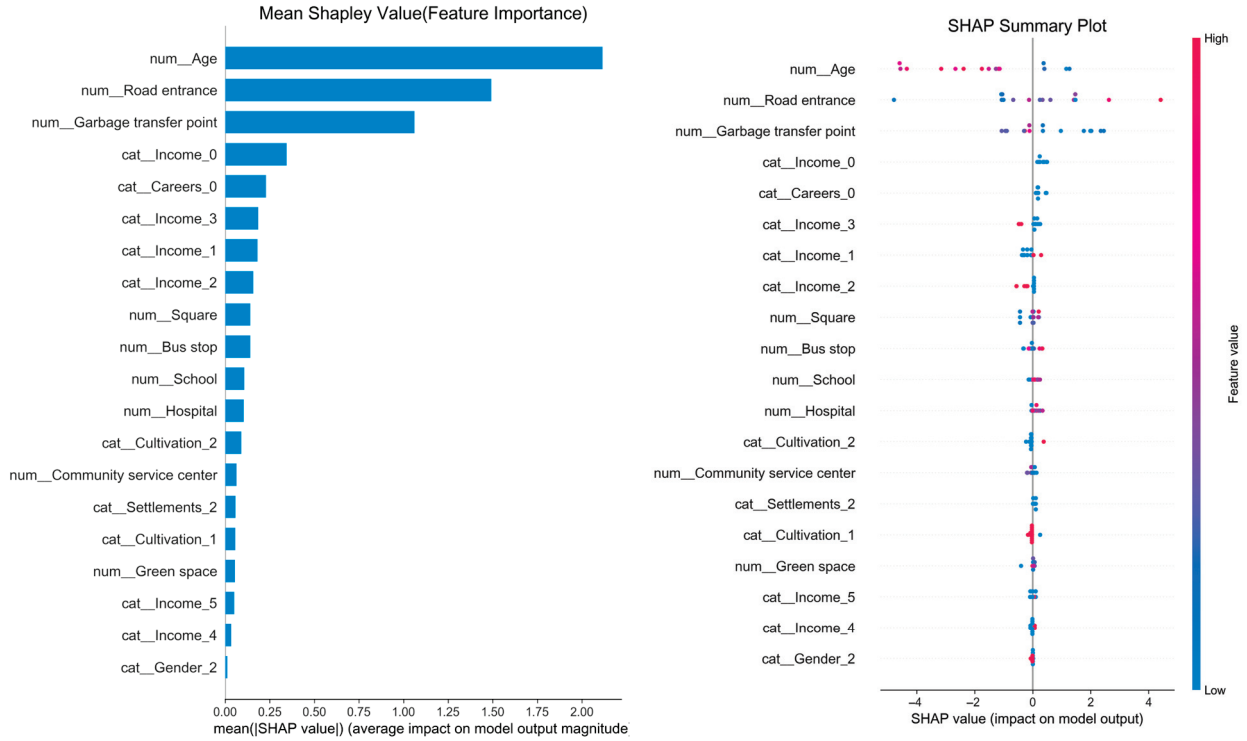
Figure 3. (**a**) SHAP feature importance bar plot for Self-Rated Health; (**b**) SHAP beeswarm plot for self-rated health.

3.4. Self-Rated Physical Health

The physical health model demonstrated performance close to that of the comprehensive health model (AUC = 0.7037, F1 = 0.7368). SHAP analysis identified age, distance to road entrance, and distance to garbage transfer point as the top three most influential features. Age remained the most important negative predictor (mean|SHAP| = 2.12). Older individuals were concentrated in the negative SHAP value region (−5 to −1) in the beeswarm plot, while younger individuals were distributed in the positive region (0 to 1), consistent with the trend observed in the comprehensive health model. Distance to road entrance ranked second in importance (mean|SHAP| = 1.49), with an overall positive mean SHAP value. The beeswarm plot showed that individuals living farther from road entrance were more likely to be predicted as healthy, whereas those living closer were concentrated in the negative region, indicating adverse effects of traffic-related environmental exposure on physical health. Distance to garbage transfer point ranked third (mean|SHAP| = 1.06). Higher distances (farther) showed positive contributions, while lower distances (closer) exhibited negative impacts, suggesting that greater distance from garbage transfer point may improve physical health, potentially due to better environmental hygiene conditions. Variables related to income level and occupation type also ranked among the top ten in importance, highlighting the significant role of socioeconomic status (SES) in physical health. Other factors, such as distance to square and bus stop, showed lower contributions but may still indirectly support health by promoting physical activity and social interaction (Table 6, Figure 4).

Table 6. SHAP Feature Importance for Self-Rated Physical Health.

Feature Name	Mean | SHAP | Value	Mean SHAP Value	Importance Rank
num__Age	2.12	−1.69	1
num__Road entrance	1.49	0.19	2
num__Garbage transfer point	1.06	0.57	3
cat__Income_0	0.34	0.34	4
cat__Careers_0	0.23	0.23	5
cat__Income_3	0.19	0.01	6
cat__Income_1	0.18	−0.14	7
cat__Income_2	0.16	−0.11	8
num__Square	0.14	−0.04	9
num__Bus stop	0.14	−0.01	10



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

Figure 4. (**a**) SHAP feature importance bar plot for Self-Rated Physical Health; (**b**) SHAP beeswarm plot for self-rated physical health.

3.5. Self-Rated Mental Health

The mental health model demonstrated relatively lower overall performance (AUC = 0.6852, F1 = 0.4615), yet SHAP results revealed several key influencing factors. Distance to school, road entrance, and community service center ranked as the top three predictors, all exhibiting negative directional effects. Both distance to school and road entrance showed the highest mean | SHAP | values (1.73). The beeswarm plot indicated that samples located closer to schools were concentrated in the negative SHAP value region (−2 to −4), while those farther away mostly exhibited positive values (0 to 2.5). Similarly, for road entrance, samples with lower distance (closer proximity) were clustered in the negative region (−6 to −3), suggesting that proximity to roads is associated with poorer mental health. Distance to community service center ranked third (mean | SHAP | = 1.59). The beeswarm plot revealed that lower distance (closer proximity) often corresponded to negative SHAP values, while higher distances (farther away) showed positive contributions, indicating that

proximity to public service facilities may, in certain contexts, contribute to psychological stress. Age remained a negative predictor in mental health outcomes, with older residents concentrated in strongly negative regions (−3 to −5) and younger individuals distributed in positive regions (0 to 1.5). The effects of distance to public squares and green space exhibited nonlinear patterns: both excessively close and excessively far distances were associated with negative contributions. Sociodemographic characteristics such as marital status and settlement status also ranked among the top ten important features, highlighting the role of social support networks in mental health (Table 7, Figure 5).

Table 7. SHAP Feature Importance for Self-Rated Mental Health.

Feature Name	Mean | SHAP | Value	Mean SHAP Value	Importance Rank
num__School	1.73	−0.62	1
num__Road entrance	1.73	−0.46	2
num__Community service center	1.59	−0.51	3
num__Age	1.48	−0.89	4
num__Square	1.45	−0.35	5
num__Green space	1.33	−0.43	6
num__Bus stop	1.22	0.08	7
cat__Settlements_1	1.10	−0.19	8
cat__Marital status_1	0.97	−0.83	9
num__Hospital	0.91	−0.28	10

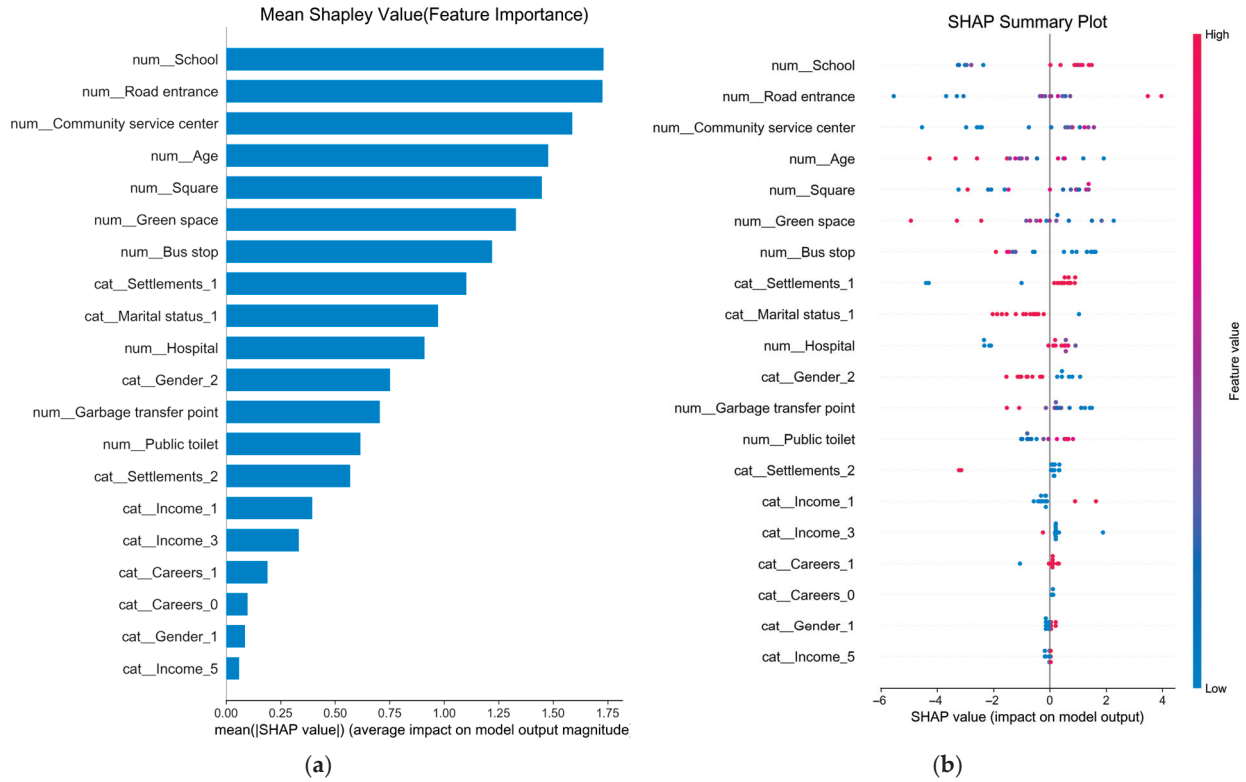


Figure 5. (**a**) SHAP feature importance bar plot for Self-Rated Mental Health; (**b**) SHAP beeswarm plot for self-rated mental health.

3.6. Self-Rated Social Health

The social health model demonstrated the weakest predictive performance (AUC = 0.5000, approaching random classification levels), suggesting that built environment accessibility plays a limited role in explaining social health outcomes. SHAP

summary results indicated that distance to road entrance and community service center ranked as the top two features, yet their mean contribution values were low, reflecting overall limited explanatory power. Other variables, such as age, distance to public square, bus stop proximity, and occupation type, also appeared among the top ten features but exhibited negligible marginal effects. Overall, social health is more likely driven by social relationships, community interactions, and cultural factors rather than physical built environment characteristics.

4. Discussion

4.1. Key Findings and Interpretation

Based on an empirical analysis of new rural communities in Pujiang County, Chengdu, this study combined GIS-measured accessibility data of nine built environment elements with self-rated health measurements, employing both GBDT modeling and SHAP interpretation methods. The research revealed that the accessibility of road entrance, public toilet, garbage transfer point, school, and community service shows a negative correlation with residents' health, though their performance varies across different health dimensions. In contrast, social health can hardly be explained by physical accessibility. The following discussion will be conducted based on model results, survey findings, and existing research.

4.1.1. Relationship Between Road Entrance and Health

The findings indicate that accessibility to road entrance is an important variable the dimensions of comprehensive health, physical health, and mental health, though its effects vary in direction and magnitude. In the comprehensive health dimension, SHAP local interpretation shows that residents living close to roads exhibit a significant negative effect in some cases, which suggests that road traffic noise, exhaust pollution, and safety risks may exert adverse impacts on residents' health [58]. This duality was further confirmed in the physical health model: residents living farther from road entrance reported higher self-rated physical health, implying that the adverse effects of environmental exposure outweigh the advantages of travel convenience. In the mental health dimension, proximity to road entrance exhibited even stronger negative effects, likely due to noise disturbance, traffic congestion, and safety concerns [59,60]. In new rural communities, it is recommended to guarantee fundamental transportation accessibility while introducing micro-level design interventions such as green buffers, noise control measures, traffic calming, and carefully planned entrance and exit points [61,62]. At the same time, macro-level strategies like relocating main access routes away from residential clusters and distributing traffic nodes more evenly should be adopted. Together, these integrated approaches can balance convenience with potential health risks, enhancing the benefits of accessibility while reducing negative environmental impacts.

4.1.2. Relationship Between Environmental Sanitation Facility and Health

Both the comprehensive health and physical health models indicate a significant negative correlation between environmental sanitation facilities—such as public toilet and garbage transfer point—and residents' health outcomes. Specifically, proximity to public toilet was associated with lower comprehensive health levels, while closeness to garbage transfer point reduced physical health ratings. This suggests that although such facilities are essential for community functioning, their NIMBY effects cannot be overlooked [63]. Prolonged exposure to unpleasant odors, pest breeding, unclean environments, and potential pathogen risks contribute to negative health perceptions among residents. This finding is consistent with existing studies, which highlight that environmental sanitation facilities

often cause resident dissatisfaction due to noise, odor, and visual pollution—factors that in turn adversely affect health perceptions [64–66]. Similarly, relevant research has found that residents living in close proximity to waste disposal facilities report significantly poorer self-rated health than those residing farther away [49,67]. These results suggest that in the planning of rural communities, the siting of sanitation facilities should not only take service coverage into account but also integrate buffer zones or strengthened environmental management measures, from a health-sensitive perspective.

4.1.3. Relationship Between Public Service Facility and Health

In the mental health model, the negative contributions of proximity to schools and community service center suggest that while educational and public service facilities provide essential social functions, they may also impose environmental pressures—including noise, congestion, and high-frequency activities—that adversely affect residents' psychological well-being. This effect may be particularly pronounced in communities with a higher proportion of elderly residents or greater demand for quiet living environments, where time-specific usage patterns can cause short-term high-intensity disturbances, thereby negatively influencing mental health assessments [58,68–70]. This finding highlights the need to balance accessibility with environmental mitigation in public service facility planning. Design-stage interventions—such as time-based traffic management, separate entrance and exit routes, activity buffer zones, and neighborhood communication mechanisms—should be introduced to reduce negative externalities for surrounding residents. The conclusion underscores the importance of integrating accessibility research with environmental quality and spatiotemporal usage patterns.

4.1.4. Social Health Cannot Be Adequately Explained by Physical Accessibility

The social health model achieved an AUC of only 0.5, indicating almost no predictive power, which implies that physical accessibility of the built environment contributes minimally to social health outcomes. Field survey results revealed that many residents considered "quality of neighborhood relationships" and "availability of collective activities" more important than the proximity to facilities. For instance, in two communities with similar levels of facility accessibility, one exhibited strong social cohesion due to residents' active participation in group dancing and volunteer services, while the other showed poorer social health outcomes resulting from insufficient neighborly interaction. This finding confirms that social health relies more heavily on social capital and cultural activities rather than spatial accessibility alone.

It aligns with existing research, which emphasizes that the core of social health lies in community cohesion and interpersonal networks [71,72]. Relevant studies focusing on the elderly population have also confirmed that social health is more strongly shaped by neighborhood support and residents' participation than by the accessibility of physical facilities [73–75]. The results of this study further build on these insights, highlighting that in new rural communities, improving social health does not rely solely on optimizing the spatial distribution of facilities; instead, the key lies in creating platforms for residents to interact and fostering a lively community culture.

4.2. Policy Implications

The findings of this study reveal that the accessibility of the built environment in new rural communities exerts both positive and negative effects on residents' health, underscoring the need for health-oriented planning that balances convenience and risk mitigation. In terms of transportation infrastructure, while proximity to road entrance improves travel and medical access, it also increases exposure to noise, vehicle emissions, and safety hazards. This suggests that road layout should be optimized by relocating

entrance appropriately and introducing green buffers to reduce environmental disturbances, while maintaining convenient external connectivity. The placement of environmental sanitation facilities also requires improvement. Proximity to public toilet and garbage transfer point was associated with poorer health outcomes, highlighting the pronounced NIMBY effects within compact community layouts. Therefore, such facilities should not be concentrated in core residential areas. Instead, spatial buffering, enclosed design, and enhanced environmental management should be implemented to minimize exposure risks. Public service facilities, such as school and community center, showed dual effects on mental health, indicating that their siting and operation should incorporate measures such as time-based management and traffic flow optimization to prevent convenience from turning into psychological stress. On the other hand, the limited explanatory power of the social health model suggests that improvements in this dimension depend more on social capital and community culture than physical proximity. Thus, the development of new rural communities should not only focus on health-oriented physical spatial provision but also strengthen social connectedness through the creation of vibrant public spaces, cultural and volunteer activities, and community self-governance mechanisms. Integrating physical environments with social interaction will more effectively promote multidimensional health outcomes.

5. Conclusions

This study examined new rural communities in Pujiang County, Chengdu, and systematically revealed the complex mechanisms through which built environment accessibility affects physical, mental, and social health. The analysis was based on residents' self-rated health measurements and network accessibility indicators of nine built environment elements, using GIS-based shortest-path calculations combined with Gradient Boosting Decision Trees (GBDT) and SHAP interpretability analysis. The key findings include the following: The accessibility of road entrance may have a negative impact on health due to noise, exhaust fumes, and safety hazards, and this impact can be verified in both physical health and mental health dimensions.; environmental sanitation facilities including public toilet and garbage transfer point exhibited clear NIMBY effects when located in close proximity; and variations in social health could not be sufficiently explained by physical accessibility alone and were more dependent on social capital, neighborhood interactions, and governance mechanisms. This study addresses a research gap in empirical studies on the built environment and health in new rural communities. By integrating refined network accessibility metrics with interpretable machine learning methods, it reveals nonlinear and localized effects of environmental factors, providing a methodological contribution and empirical evidence to support replicable evaluation frameworks.

Despite these insights, several limitations remain. First, the limited sample size and single-region focus (Pujiang County) constrain the generalizability and subgroup analysis capabilities of the results. Future studies should expand the sample size and include multi-regional comparisons to enhance external validity. Second, while the GBDT model and SHAP method effectively captured nonlinear relationships and variable importance, they fell short of establishing strict causal mechanisms and did not fully account for spatial dependence. Future research could advance in several directions: data enhancement includes integrating multi-source data such as big mobility data, remote sensing imagery, and health records; in terms of methodological refinement, multi-model cross-validation and causal inference approaches should be adopted to improve robustness; in the aspect of indicator, future research may shift from a purely "distance-oriented" approach to one that incorporates "quality and perception-oriented" metrics to better reflect residents' actual experiences. Causal and spatial analysis can introduce causal inference frameworks (e.g.,

instrumental variables or natural experimental designs) and spatial heterogeneity models to strengthen interpretability and mechanism identification.

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Institutional Review Board Statement: The survey in this study has obtained IRB approval under the ethical review approval number WHU-NS-IRB2023007. The approval document is retained for verification and can be provided in full for journal review. This study was conducted strictly in line with the IRB-approved protocol, complying with ethical standards and regulatory requirements to fully protect participants' rights, interests and privacy.

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

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. Questionnaire on Healthy Development in New Rural Community

Dear Residents,

Greetings!

We are the "Healthy Rural Area Investigation" research team from Wuhan University. Through this questionnaire, we aim to understand your and your village's basic information. All responses will be used solely for research purposes, and real names will not be recorded. We kindly ask you to answer truthfully. Unless otherwise specified, please select only one option per question by marking $\surd$ next to your choice. For open-ended questions, please write your answer on the provided line. Based on the results of this survey on healthy community development, we will propose recommendations for further improving the living environment in your community. We sincerely hope you can provide accurate responses and complete the questionnaire promptly. Thank you very much for your support! Wishing you success in your work and happiness in your family.

Contact Persons:

Li Kehao: 15136819377

Liu Chao: 13129952835

July 2023

I. Individual Characteristics

1. Your gender: _____, Your age: _____ years old, Your occupation:

(1) Farmer (2) Government employee (3) Self-employed individual

(4) Worker (5) Other

2. Your marital status:

(1) Unmarried (2) Married (3) Divorced (4) Widowed

3. The house number of your current residence: Village _____ Number _____

4. Your status:

(1) Local permanent resident (2) Settled non-local resident

5. You have lived in this village for _____ years. Your current primary residence is:

(1) Old family home (2) New rural community (3) Residence in county town or other urban area

6. Your household has _____ members. Last year, your total annual household income was as follows:

(1) <¥50,000 (2) ¥50,000–¥100,000 (3) ¥100,000–¥200,000

(4) >¥200,000

7. Does your household still engage in farmland cultivation?

(1) Yes, still cultivating farmland (2) No, no longer cultivating farmland

II. Self-Rated Health Scale Survey

Instructions:

This scale consists of 48 questions concerning your experiences over the past four weeks. Below each question is a scale divided into 10 increments. Please mark an "×" at the position that best reflects your situation for each item. (Note: Only one "×" per scale.)

Example:

How would you describe your sleep?

Very poor 0–1–2–3–4–5–6–7–8–9–10 Very good

(0: very poor sleep; 10: very good sleep; between 0 and 10: closer to 0 indicates worse sleep, closer to 10 indicates better sleep.)

Questions:

1. How would you describe your eyesight?

Very poor 0–1–2–3–4–5–6–7–8–9–10 Very good

2. How would you describe your hearing?

Very poor 0–1–2–3–4–5–6–7–8–9–10 Very good

3. How would you describe your appetite?

Very poor 0–1–2–3–4–5–6–7–8–9–10 Very good

4. Do you often experience gastrointestinal discomfort (e.g., bloating, diarrhea, constipation)?

Very often 0–1–2–3–4–5–6–7–8–9–10 Never

5. Do you get tired easily?

Very easily 0–1–2–3–4–5–6–7–8–9–10 Not easily

6. How would you describe your sleep?
Very poor 0–1–2–3–4–5–6–7–8–9–10 Very good

7. Do you experience pain of varying intensity?
Very often 0–1–2–3–4–5–6–7–8–9–10 Never

8. Do you have difficulty dressing yourself?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

9. Do you have difficulty grooming yourself?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

10. Do you have difficulty performing daily household chores?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

11. Can you go shopping alone for daily items?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

12. Do you have difficulty eating by yourself?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

13. Do you have difficulty bending or kneeling?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

14. Do you have difficulty climbing up or down at least one flight of stairs?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

15. Do you have difficulty walking half a li (0.25 km)?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

16. Do you have difficulty walking three li (1.5 km)?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

17. Do you have difficulty engaging in high-energy activities (e.g., intense exercise, farm labor, moving heavy objects)?
Very difficult 0–1–2–3–4–5–6–7–8–9–10 Not difficult

18. Overall, how would you rate your physical health compared to your peers?
Much worse 0–1–2–3–4–5–6–7–8–9–10 Much better

19. Do you feel optimistic about the future?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

20. Are you satisfied with your current life situation?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

21. Do you feel confident in yourself?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

22. Do you feel safe in your daily living environment?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

23. Do you feel happy?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

24. Do you feel mentally tense?
Very much 0–1–2–3–4–5–6–7–8–9–10 Not at all

25. Do you feel downhearted or low in spirit?
Very much 0–1–2–3–4–5–6–7–8–9–10 Not at all

26. Do you feel afraid without reason?
Very much 0–1–2–3–4–5–6–7–8–9–10 Not at all

27. Do you repeatedly check things you have done to feel assured?
Very much 0–1–2–3–4–5–6–7–8–9–10 Not at all

28. Do you feel lonely even when you are with others?
Very much 0–1–2–3–4–5–6–7–8–9–10 Not at all

29. Do you feel restless or unsettled?
Very much 0–1–2–3–4–5–6–7–8–9–10 Not at all

30. Do you feel empty, bored, or that life lacks meaning?
Very much 0–1–2–3–4–5–6–7–8–9–10 Not at all

31. How would you describe your memory?
Very poor 0–1–2–3–4–5–6–7–8–9–10 Very good

32. Can you concentrate easily on one task?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

33. How would you describe your ability to think or handle problems?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

34. Overall, how would you rate your mental health?
Very poor 0–1–2–3–4–5–6–7–8–9–10 Very good

35. Can you properly handle unpleasant things that happen in your life, studies, or work?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very well

36. Can you adapt quickly to new living, learning, or working environments?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very well

37. How do you evaluate the roles you take in work, study, and life?
Very poorly 0–1–2–3–4–5–6–7–8–9–10 Very well

38. Is your family life harmonious?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very well

39. Do you have many close colleagues, classmates, neighbors, relatives, or partners?
Very few 0–1–2–3–4–5–6–7–8–9–10 Very many

40. Do you have friends with whom you can share joys and sorrows?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

41. Do you discuss issues with your friends or relatives?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very often

42. Do you regularly stay in touch with relatives and friends (e.g., visits, phone calls, messages)?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very often

43. Do you often participate in social or group activities (e.g., party/league gatherings, unions, student associations, religious events, friend meetups, sports, entertainment)?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very often

44. Can you rely on your family for help when needed?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

45. Can you rely on your friends for help when needed?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

46. When facing difficulties, do you actively seek help from others?
Not at all 0–1–2–3–4–5–6–7–8–9–10 Very much

47. Overall, how would you rate your social functioning (e.g., interpersonal relationships, social interactions) compared to your peers?
Much worse 0–1–2–3–4–5–6–7–8–9–10 Much better

48. Overall, how would you rate your health compared to your peers?
Much worse 0–1–2–3–4–5–6–7–8–9–10 Much better

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