land

Special Issue Reprint

Ecosystem Services and Urban Green Spaces

Planning, Policy Development and Governance Implications

Edited by
Luca Battisti, Fabrizio Aimar and Federico Cuomo

mdpi.com/journal/land

MDPI

Ecosystem Services and Urban Green Spaces: Planning, Policy Development and Governance Implications

Ecosystem Services and Urban Green Spaces: Planning, Policy Development and Governance Implications

Guest Editors

Luca Battisti
Fabrizio Aimar
Federico Cuomo

MDPI

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

Guest Editors

Luca Battisti
Department of Cultures,
Politics and Society
University of Turin
Turin
Italy

Fabrizio Aimar
Department of Architecture
Texas A&M University
College Station
USA

Federico Cuomo
School of Management
Polytechnic of Milan
Milan
Italy

Editorial Office

MDPI AG
Grosspeteranlage 5
4052 Basel, Switzerland

This is a reprint of the Special Issue, published open access by the journal *Land* (ISSN 2073-445X), freely accessible at: https://www.mdpi.com/journal/land/special_issues/C91W5AL2ZT.

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

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

ISBN 978-3-7258-3173-9 (Hbk)
ISBN 978-3-7258-3174-6 (PDF)
https://doi.org/10.3390/books978-3-7258-3174-6

Contents

About the Editors

Luca Battisti

Luca Battisti, who has a PhD in Agricultural, Forestry and Agri-Food Sciences, specialised in the analysis and evaluation of ecosystem services provided by the landscape and urban horticulture. He is a research fellow in Economic-Political Geography at the University of Turin (Italy). Since 2021, he has been involved in European projects concerning the study and implementation of nature-based solutions within cities and urban food system transformations through innovative Living Labs implementations. He is the lecturer in 'Cartography, Mapping, and GISs in International Cooperation' at the University of Turin.

Fabrizio Aimar

Fabrizio Aimar is an architect, earning a Ph.D. with honors in Urban and Regional Development from the Polytechnic University of Turin, Italy. He has been an assistant professor of practice in the Department of Architecture at Texas A&M University, USA. At the same university, he also serves as the Director of the Center for Heritage Conservation and holds the Woodcock Endowed Professorship in Historic Preservation. Previously, he served as a lecturer and the Head of the Department of Architecture and Civil Engineering at the Faculty of Architecture and Design at POLIS University, Tirana, Albania (2021–2023). His research interests cover urban resilience, landscape resilience and planning, cultural heritage, and sustainable architecture.

Federico Cuomo

Federico Cuomo is a postdoctoral researcher in policy analysis at the University of Turin and a researcher at IRES (Istituto di ricerche socio economico della Regione Piemonte). In 2022, he obtained a PhD in Innovation for the circular economy. He carried out short-term research visits in Amsterdam, Budapest, and Madrid. Adopting a policy analysis perspective, his research interests range from collaborative and multilevel governance to urban experimentations, protected area management, and co-production in public policy.

Preface

This Special Issue will focus on investigating urban green spaces as transformative contexts where alternative collaborative governance arrangements can deliver ecosystem services by engaging with local communities. Taking into account different viewpoints, this Special Issue will deepen the capacity of urban spaces to provide experimental settings to co-produce innovative solutions for urban living and planning based on sustainability and inclusivity.

To this extent, Xiaoqi Feng and colleagues discuss the case of Sydney (Australia) to delve into the relationship between fatal traffic crashes and street tree percentages. They demonstrate that reducing speed limits to below 70 km/h can save lives and potentially mitigate the risks of severe or fatal traffic accidents involving street trees, thereby contributing to the creation of greener, cooler, and healthier urban environments.

Bilyana Borisova and colleagues focus on identifying urban properties suitable for urban green infrastructure interventions, optimizing natural regulatory functions to achieve long-term pollution mitigation and a reduction in secondary dust levels.

Henri Kabanyegeye and colleagues conduct an analysis of the dynamics of green infrastructure in the cities of Bujumbura, Kinshasa, and Lubumbashi, identifying distinct patterns of green infrastructure development across these urban contexts. Based on their findings, they conclude that urban growth in these cities requires careful planning to ensure the effective integration of adequate green infrastructure, thereby promoting environmental sustainability and enhancing urban resilience.

In their study, Yu Li and colleagues adopt a comprehensive approach to ecological functional zoning in the Shenzhen region of China. By integrating advanced geospatial analysis tools, diverse data sources, and sophisticated statistical methods, the research identifies and categorizes various ecological functions. These functions are delineated based on a robust set of indicators and spatial analysis techniques, providing a nuanced understanding of the region's ecological dynamics.

Yiwen Cui and colleagues conduct an investigation into the challenges and opportunities associated with community engagement initiatives, specifically focusing on New Zealand's major ethnic groups, including New Zealand Europeans, Māori, Chinese, and Pasifika. Richa Sharma and colleagues investigate the spatio-temporal impacts of land use and land cover changes on both the provision and monetary value of above- and below-ground carbon sequestration and storage in Noida, focusing on the years 2011, 2019, and a simulated projection for 2027.

Dragan Vujičić and colleagues identify the key barriers and drivers influencing the regulatory framework of green infrastructure, drawing on the perspectives of 352 professionals surveyed between 2018 and 2023 in Serbia.

Davide Marino and colleagues conduct a comprehensive literature review to identify the biophysical and economic coefficients associated with ecosystem services provided by different land cover classes. These coefficients are compiled in a database to assess changes in ecosystem service supply, considering permanence and transition phenomena in Italy from 1990 to 2018.

Tomomi Funahashi and Shozo Shibata examine the historical dynamics of forested areas and their associated cultural values from the late 19th century onwards. This study focuses on 15 shrine/temple forests situated in the mountainous and foothill regions of Kyoto City. The analysis utilizes geographical information systems (GISs), leveraging topographic maps and aerial photographs to investigate these forests' evolution over time.

Liwei Qin and colleagues explore the spatial heterogeneity of park vitality across various urban landscapes at the city scale, addressing the limitations of traditional approaches to understanding the dynamics of park vitality.

Zihan Cai and colleagues, through quantitative analysis of the spatio-temporal evolution patterns of Urban Park Green Areas, identify the driving mechanisms behind these changes and provide policy recommendations for planning and management, informed by performance evaluation outcomes.

Finally, Qian Xu and colleagues select Guangdong Province in China as a case study to examine the trade-offs and synergies between various ecosystem services, as well as to investigate the underlying mechanisms influencing these relationships in economically developed regions with high population density.

By integrating theoretical perspectives with empirical research, this Special Issue provides valuable insights for researchers, practitioners, and policymakers seeking to advance the development of urban green spaces that effectively co-produce ecosystem services in response to the needs of local communities.

Luca Battisti, Fabrizio Aimar, and Federico Cuomo

Guest Editors

land

Article

The Transition of Forest Cover and Its Cultural Values in Shrine/Temple Forests in the Mountainous and Foothill Areas of Kyoto City: A Study Based on Topographic Maps and Aerial Photos

Tomomi Funahashi * and Shozo Shibata

Graduate School of Global Environmental Studies, Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan; shibata.shozo.6n@kyoto-u.ac.jp
* Correspondence: funahashi.tomomi.74e@st.kyoto-u.ac.jp

Abstract: There is growing interest in the diverse roles of forests in addressing climate change and biodiversity goals. Recent studies have indicated a disregard for the cultural values of forests that have been formed in close association with human activities. This may potentially lead to the loss of cultural characteristics, traditional forest knowledge, and biodiversity. This study explores historical forest dynamics and their unique cultural values from the end of the 19th century in 15 shrine/temple forests located in the mountainous and foothill areas of Kyoto city. Using geographical information systems (GIS) based on topographic maps and aerial photographs, this study investigates the forest composition in the 1890s, 1980s, and from 2010. The results indicate that approximately half of the targeted shrine/temple forests were composed of low *Pinus densiflora* forests and coppice forests in the 1890s. Between the 1890s and 1910s, coniferous forests were planted in these areas with the intention of land conservation and timber production. This distinctive forest cover became a typical characteristic for shrine/temple forests until the 1980s. However, from the 1980s, a decrease in the cultural value of shrine/temple forests was observed due to the lack of human activities in these forests. As a result, the distinction between shrine/temple forests and the surrounding forests has become blurred. This could potentially cause the homogenization of cultural characteristics. This study aims to inform readers of the cultural value associated with the historical landscape and biodiversity found in shrine/temple forests.

Keywords: forest history; forest landscape; cultural forest; *Pinus densiflora*; planted forest; GIS

Citation: Funahashi, T.; Shibata, S. The Transition of Forest Cover and Its Cultural Values in Shrine/Temple Forests in the Mountainous and Foothill Areas of Kyoto City: A Study Based on Topographic Maps and Aerial Photos. *Land* **2023**, *12*, 2096. https://doi.org/10.3390/land12122096

Academic Editors: Fabrizio Aimar and Federico Cuomo

Received: 31 October 2023
Revised: 19 November 2023
Accepted: 20 November 2023
Published: 22 November 2023

1. Introduction

1.1. Research Background

There is a growing interest in the diverse roles of forests in addressing climate change and biodiversity goals. The United Nations declared 2021 to 2030 to be the "Decade on Ecosystem Restoration", with focused efforts on promoting forest restoration [1]. Apart from the increasing expansion of forested areas, there is an urgent need to enhance the natural characteristics of forests, based on the assessment of forest ecosystem services [2]. In this context, old plantation forests that are not utilized would, over time, deliver environmental benefits more effectively if they were restored to natural forest or semi-natural forests [3]. On the other hand, there is also the practice of maintaining the characteristics of forests that have been shaped by ongoing human activities through historical evidence. An example of such a practice can be found in Italy's coppice woodlands [4]. This Italian approach argues that forest management practices must consider the historical context to avoid endangering the cultural value of these forests [4]. According to the theories related to ecosystem services, cultural values have been associated with the "aesthetic, artistic, educational, spiritual and/or scientific values of ecosystems" [5]. However, these assessments are from the perspective of the recipients of these services, and they may not encompass the cultural values influenced by human actions such as forest management policies and operational activities [2]. Traditional forest management practices applied for centuries have significantly influenced forest characteristics (in terms of extension, density, species composition, and vertical and horizontal structure). Even if traditional forest management practices are seldom practiced today, the influence of past management practices continues to shape the current characteristics of forests [4]. Therefore, to neglect the cultural aspects of forests carries the risk of the future homogenization of forest types, and the loss of cultural significance, traditional forest knowledge, and biodiversity on a landscape scale [4].

In Japan, the Satoyama Initiative [6] promotes conservation efforts to establish land use systems that respect traditional knowledge while fostering a harmonious relationship between nature and human activities. These efforts have also involved the assessment and management of ecosystem services, including the diversity of secondary natural environments [7].

Moreover, "shrine/temple forests" in Japan are forests that are owned or utilized by shrines or temples and formed in close association with human activities [8]. Originally, these forests were held for the purpose of maintaining the religious ambience and management of shrines and temples. They served as places to foster religious solemnity, conduct rituals and practices, and functioned as disaster prevention areas [9,10]. In addition, shrine/temple forests have historically served as a source of income for shrines and temples through the production of timber and non-timber forest products (NTFPs) [9,10]. Therefore, shrine/temple forests can be described as green environments that exhibit various functions that align with the needs and requirements of shrines or temples, including landscaping, land conservation, timber production, and NTFP production [8].

Recent studies on shrine/temple forests have presented varying perspectives regarding their historical characterization. Miyawaki (1970) [11] considers these forests to be primeval and left undisturbed by human intervention. In contrast, other researchers have indicated that until the Meiji period (mid-19th century), coniferous forests, managed for the extraction of forest resources, constituted the core of shrine/temple forests [12–14]. Moreover, the current deciduous broad-leaved forests are suggested to comprise secondary forests that emerged after the Meiji period (mid-19th century) [12–14]. Such research is instrumental in guiding the discourse and management strategies that consider the multifaceted historical significance of these forests.

Due to the differences in perception regarding the historical significance of shrine/temple forests, little research has focused on shrine/temple forests and their cultural values, influenced by human activities [15]. Therefore, this study utilizes the discourse propounding that shrine/temple forests in Japan are forests formed under the influence of active human activities.

1.2. The Shrine/Temple Forests

The shrine/temple forests observed today have a historical background, and have been influenced by events that occurred after the Meiji Restoration (1868). Primarily, they were influenced by the "Land Tax Reform" in 1875, whereby most of the shrine/temple forests became nationalized [9,10]. However, the "National Forests Act" in 1898 and the "Disposal of Former Shrine and Temple Reserve Forest" in 1947 resulted in the return of certain areas to the original shrines and temples [15]. As a result, through these historical processes, the boundaries and extent of the current shrine/temple forests were determined.

Between the 1890s and 1920s, the management system for shrine/temple forests began to take shape within the Japanese government. Scholars such as Honda Seiroku, Hongo Takanori, and Uehara Keiji developed the concept of "*Shaji Fuchirin Ron (Management Theory of Shrine/Temple Forest)*", from the perspectives of forestry and landscape architecture [16]. This concept advocated for the ideal aesthetic qualities of shrine/temple forests, emphasizing the cultivation of religious ambience through the planting of evergreen coniferous trees, such as *Cryptomeria japonica* and *Chamaecyparis obtusa*. These trees are valued as construction materials for shrine/temple buildings and as general timber. However, they recognized that maintaining these coniferous trees in urban areas with a high population density and ongoing industrialization would become unfeasible. As an alternative, a proposal for maintaining shrine/temple forests could be the natural regeneration of evergreen broad-leaved trees such as *Cyclobalanopsis*, *Castanopsis*, and *Cinnamomum camphora*. Promoting the preservation of evergreen broad-leaved forests marked a significant milestone in the concept of shrine/temple forest landscape [17].

1.3. The Historical Landscape and Forest Dynamics in Kyoto City

Kyoto was the imperial capital of Japan from its foundation until the middle of the 19th century. As the center of Japanese culture for more than 1000 years, Kyoto illustrates the development of Japanese wooden architecture, particularly shrine/temple architecture [18]. In Kyoto city, shrine/temple forests have been recognized as essential elements that contribute to the historical landscape of shrine/temple historical sites and architecture [18]. Since the Meiji period (1868–1912), efforts have been made to preserve forest landscapes as tourist resources and local scenery, focusing on nationalized shrine/temple forests in the suburbs of Kyoto city such as Higashiyama and Arashiyama [19–21]. Ogura (1992) [22] and Nakajima (1996) [23] conducted detailed examinations of the vegetation surrounding Kyoto city during the mid-Meiji period (1890s) by using a topographical map with a scale of 1/20,000, surveyed by the Land Survey Department of Japan's Army in 1889 (Annotation A1 in Appendix A). These studies found that around the urban areas of Kyoto, there were widespread *Pinus densiflora* forests, with a height of less than 2.7 meters (m). On the other hand, the background of shrines and temples consisted of *Pinus densiflora* forests greater than or equivalent to 5.4 m, while the more remote areas in the mountainous northern part of Kyoto consisted mainly of *Cryptomeria japonica* forests. These studies highlighted that these forests constituted distinctive landscapes associated with shrine/temple forests in the 1890s.

During the Meiji period (1868–1912), forest landscapes were generally preserved; however, the excessive logging during World War II destroyed these forest landscapes [24]. However, also during World War II, shrine/temple forests were protected from this excessive logging due to their religious significance [24]. This exemption from excessive logging provided the forest stands with continuity for over 75 years, which was revealed in the 1980s shrine/temple forest survey [25]. Until the 1980s, secondary forests primarily composed of *Pinus densiflora* continued to play a central role in shaping the scenic beauty of the ancient capital, Kyoto city [26]. *Pinus densiflora* forests surrounding the city of Kyoto have been utilized throughout history as a source of construction materials, fuelwood, and food (such as mushrooms), and have promoted maintenance practices like underbrush clearing and leaf raking [27]. However, with the decline in its utilization due to the fossil fuel revolution, coupled with the outbreak of pine wilt disease, *Pinus densiflora* has experienced a rapid decline in its numbers since the 1980s [28]. Pine wilt disease (PWD) is caused by *Bursaphelenchus xylophilus*, the pine wood nematode (PWN) [29,30]. It has caused serious forest issues primarily in East Asia [31] since the 1970s, with serious outbreaks in China, Korea and Taiwan [32–34]. Across Japan, except for certain areas of Hokkaido, it became a nationwide outbreak [31]. The PWD rapidly became prevalent in Kyoto [28] during the 1980s, resulting in a change in the forest landscapes surrounding Kyoto city. By the late 1990s, forests consisting of *Pinus densiflora* were being naturally replaced by maturing understory trees, and the natural regeneration of *Pinus densiflora* forests became unfeasible in areas that ceased the thinning and mowing of forest undergrowth [28,35]. Eventually, *Pinus densiflora* forests were replaced by broad-leaved forests mainly with *Quercus variabilis* and *Quercus serrata* [35,36]. Currently, the distribution of *Castanopsis cuspidata* is expanding [36]. *Castanopsis cuspidata* is an evergreen broad-leaved tree and is known as a climax species in most areas of Japan, including Kyoto city [37]. In the temperate regions of Japan, there have been reports suggesting that secondary forests have a higher biodiversity compared to climax forests [36,38,39]. These changes have also affected shrine/temple forests, and consequently, resulted in a growing need for the conservation and restoration of historical forest landscapes [24,40].

Conservation efforts have been undertaken to preserve the historical landscape centered around *Pinus densiflora* forests, encompassing the entire forest area surrounding Kyoto city [24,35]. However, approximately 42% of shrine/temple forests in Kyoto city are occupied by planted coniferous forests of *Cryptomeria japonica* or *Chamaecyparis obtusa* [41]. There are no specific policies that encompass the preservation of planted coniferous forests of *Cryptomeria japonica* or *Chamaecyparis obtusa* [24,40]. Although shrine/temple forests have been managed for various purposes, including the preservation of religious solemnity and as a source of timber resources for shrines and temples [9,10], human activities in shrine/temple forests are different when compared to non-shrine/temple forests in Kyoto city. As a result, there is a need to develop explicit policies that target the conservation and restoration of shrine/temple forests whilst considering the cultural value of the forest landscape.

1.4. Research Questions

Previous studies on shrine/temple forests in Kyoto city have primarily focused on (i) the landscape conservation policies implemented during the Meiji period (1868–1912) [42,43], (ii) the ecological value of forests [44,45], (iii) on examining the vegetation and resource utilization of a specific shrine during the Edo period (1603–1868) [13,14]. For example, studies conducted by Ogura (1992) [22] and Ogura (2012) [46] regarding the vegetation of shrine/temple forests in Kyoto city focused only on the Meiji period (1868–1912). However, investigations into the changes in the forest cover of shrine/temple forests and the reasoning behind planting coniferous forests of *Cryptomeria japonica* or *Chamaecyparis obtusa* since end of the 19th century are lacking. Furthermore, the cultural values implicated in each of these processes have not been clarified.

Therefore, in this study, the following two research questions were established to investigate the conservation of cultural values in shrine/temple forests in Kyoto city.

Q1. How has the forest cover of shrine/temple forests in Kyoto city changed since the mid-Meiji period (1890s)?

Q2. What is the history of the cultural values held by shrine/temple forests in Kyoto city since the mid-Meiji period (1890s)?

2. Materials and Methods

2.1. Study Sites

This research focuses on 15 shrine/temple forests located within Kyoto city (Figure 1). These 15 sites were selected based on the "Survey for the Identification of Outstanding Shrine/Temple Forests in Kyoto Prefecture" [25] (Annotation A2 in Appendix A), conducted by the Kyoto Prefectural Government in 1988–1989 (hereinafter referred to as the "Kyoto Prefectural Shrine/Temple Forest Survey"). In this survey, the selection of these forests was based on five criteria, which are listed in Table 1. The scope of this study encompasses the shrine/temple forests specified in the survey report, with a focus on the historical changes in forest cover from the past to the present. It is important to note that these boundaries do not necessarily represent the current ownership boundaries of the shrines and temples. Additionally, certain areas might not be part of the forest that was owned by shrines and temples during the Meiji era (1868–1912) because of the nationalization of temple forests under the "Land Tax Reform" in 1875. In this study, we conducted an analysis of the forest cover changes in the shrine/temple forests, taking into consideration the surrounding forest environment. To ensure consistency in the sample size of the dataset, buffer zones of the same area were established around each shrine/temple forest.

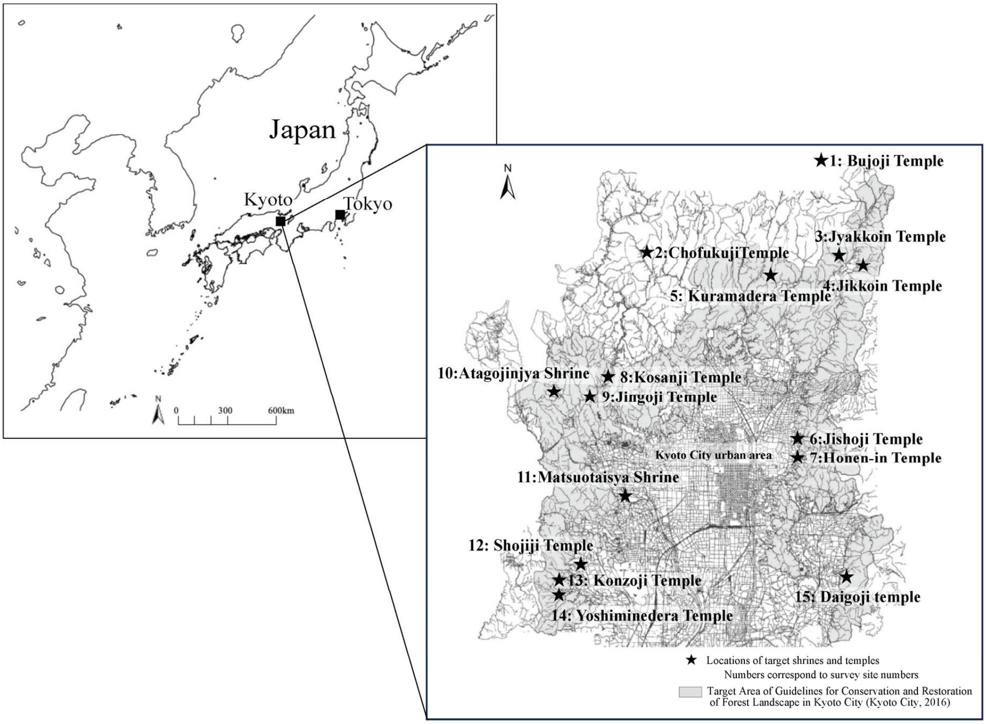

Figure 1. The locations of the 15 shrine/temple forests in Kyoto city, using the base map from "Guidelines for Conservation and Restoration of Forest Landscape in Kyoto City" [24].

Table 1. Selection criteria for the "Kyoto Prefectural Shrine/Temple Forest Survey" [25].

	Selection Criteria
1	Primeval or near-pristine natural forest
2	Forest communities that represent the local landscape and shows typical community characteristics
3	Forests where no logging has occurred over the long term
4	Natural forests that are scientifically valuable because of their unique distribution under natural conditions or because they show typical transitional forms.
5	Forested areas of 1 ha or more and with forest age of 75 years or older

Among the 15 shrine/temple forests, No. 1, No. 2, and No. 10 are located at elevations from 500 to 900 m, while the other shrine/temple forests are all located at elevations below 500 m (Figure 1).

2.2. Research Method

In this study, we examined changes in the forest cover of Kyoto using data from three different periods: (i) the 1890s, which has been commonly studied for historical forest landscape analysis in Kyoto city; (ii) the 1980s, a period known for changes in forest composition, including a decline in *Pinus densiflora* forests; and (iii) after 2010, as the present day. The 1980s field-survey-based vegetation data were used as an intermediate indicator from the 1890s to the present in order to minimize errors due to the interpretation of aerial photographs [47]. As indicated earlier, the forest landscape in Kyoto city remained largely unchanged from the 1890s until the 1980s [35]. Additionally, due to the lack of available historical data for other periods [46], these three periods were selected for the analysis of this study.

Aerial photographs have been widely used for long-term forest cover comparisons due to the relatively small difference in data acquisition accuracy between them and satellite images [47–49]. However, due to the historical context of this study, topographical maps were also utilized to understand the vegetation during the 1890s [22,46,50]. Therefore, this study used a combination of topographic maps and aerial photographs (Table 2, Figure 2) as primary data sources and referred to a vegetation map obtained from GIS data. The GIS vegetation maps were from the "3rd Natural Environment Survey on Vegetation" (1/50,000 scale, conducted in 1983) and the "6th and 7th Natural Environment Survey on Vegetation" (1/25,000 scale, conducted in 2004), provided by the Ministry of the Environment to aid in the interpretation of vegetation patterns. As historical resources from the 1890s, we used a topographical map with a scale of 1/20,000 surveyed in 1889 and a topographical map with a scale of 1/20,000 surveyed in 1893 (Annotation A3 in Appendix A) to understand the vegetation during the Meiji period (1890s) [22,46,50]. For the 1980s and after 2010, we utilized three major sources of aerial photographs: (i) the 1985 National Land Image (color aerial photograph taken by the Geospatial Information Authority of Japan (GSI)) with a scale of 1/20,000; (ii) the 2010 National Land Image (color aerial photograph taken by the GSI) with a scale of 1/10,000; and (iii) the 2020 National Land Image (color aerial photograph taken by the GSI) with a scale of 1/10,000 (Annotation A4 in Appendix A). In addition, the study utilized supporting data from the 2008 Digital National Land Information, published by the GSI (Orthoimage) and with a ground pixel size of 40 cm, as a reference for ArcGIS (ver. 3.1.0) georeferencing. This allowed the study to perform geometric correction for these aerial photographs before conducting the identification of the forest cover type. Moreover, geographical location information was added to these topographic maps by employing the Digital National Land Basic Map (Basic Geospatial information) for reference and for the utilization of georeferencing. The positions of shrine/temple buildings primarily served as the starting points for this process. Subsequently, three vegetation maps were created using the planar rectangular coordinate system JGD2000 VI as the basis.

Table 2. Data sources used for forest cover type mapping.

Period	Survey Site Numbers	Reference	Year	Publisher
1890s	1, 2	the topographical map surveyed in 1893 with a scale of 1/20,000	1893	Land survey department of Japan's Army
	3–15	the topographical map surveyed in 1889 with a scale of 1/20,000	1889	Land survey department of Japan's Army
1980s	3–15	the 1985 National Land Image (color aerial photograph) with a scale of 1/20,000	1985	the Geospatial Information Authority of Japan (GSI)
After 2010	1, 2	the 2010 National Land Image (color aerial photograph) with a scale of 1/10,000	2010	the Geospatial Information Authority of Japan (GSI)
	3–15	the 2020 National Land Image (color aerial photograph) with a scale of 1/10,000	2020	the Geospatial Information Authority of Japan (GSI)

The topographical map with a scale of 1/20,000 surveyed in 1889 was created for military purposes, with the Japanese army aiming to perform assessments to locate construction timber and fuelwood resources [22]. Therefore, the classification of forests on the map was primarily performed from the perspective of resource utilization. This classification was performed based on tree species with a high timber value, including *Cryptomeria japonica*, *Chamaecyparis obtusa*, and *Pinus densiflora*, as well as tree species with a high fuelwood value, including *Quercus serrata* or *Quercus acuta*, and coppice forests. For *Cryptomeria* *japonica*, *Chamaecyparis obtusa*, and *Pinus densiflora*, subcategories of mature or low-height trees were assigned. In the study area of this research, only *Pinus densiflora* had a distinction between mature and low-height trees, which resulted in the use of the classifications shown in Figure 3. When considering the influence of historical human activities, it is considered inadequate to evaluate the cultural value solely based on classifications derived from phytosociology [2]. To prevent this bias in the study, we used the resource-use-based forest classifications obtained from topographic maps created in the Meiji period as a basis for reading aerial photographs in the 1980s and after 2010. Figure 3 illustrates the correlation between the corresponding legend of these topographical maps and identifies the vegetation types from these aerial photographs. The symbols used in the topographical maps and their corresponding vegetation are in reference to Ogura (1992) [22] and Ogura (2012) [46]; these were verified in detail based on old photographs and geographical records.

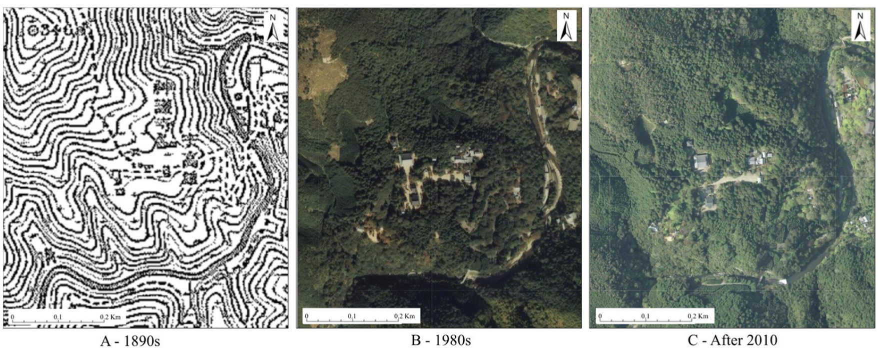

Figure 2. Images of the data sources used for forest cover type mapping. (**A**) Excerpt from the topographical map surveyed in 1889 by the land survey department of Japan's Army, with a scale of 1/20,000. (**B**) Excerpt from the 1985 National Land Image obtained by the Geospatial Information Authority in Japan, with a scale of 1/20,000. (**C**) Excerpt from the 2020 National Land Image obtained by the Geospatial Information Authority in Japan, with a scale of 1/20,000.

Considering the potential natural vegetation in Kyoto city, it is known that all *Cryptomeria japonica* forests shown on the topographic map were established through afforestation [51]. Therefore, these *Cryptomeria japonica* forests on the topographic map corresponded to the planted coniferous forests observed in the aerial photographs. However, distinguishing between mature and low *Pinus densiflora* forests on the topographic map was not feasible in the aerial photographs. For this reason, both types were combined and classified as *Pinus densiflora* forests. It should be noted that the coppice forests found on the topographic map could not be identified as only coppice forests in the aerial photographs from the same period. Therefore, these coppice forests were aligned with natural conifer and broad-leaved mixed forests.

Apart from planted conifer forests of *Cryptomeria japonica* or *Chamaecyparis obtusa*, and the secondary forests of *Pinus densiflora*, the existing vegetation in Kyoto City includes broad-leaved trees such as *Castanopsis* spp. and *Quercus* spp. at elevations below 500 m [52]. On the other hand, at elevations between 500 m and 1000 m, the existing vegetation includes broad-leaved trees such as *Quercus* spp. and *Acer* spp., as well as natural coniferous trees such as *Abies firma* and *Chamaecyparis obtuse* [52].

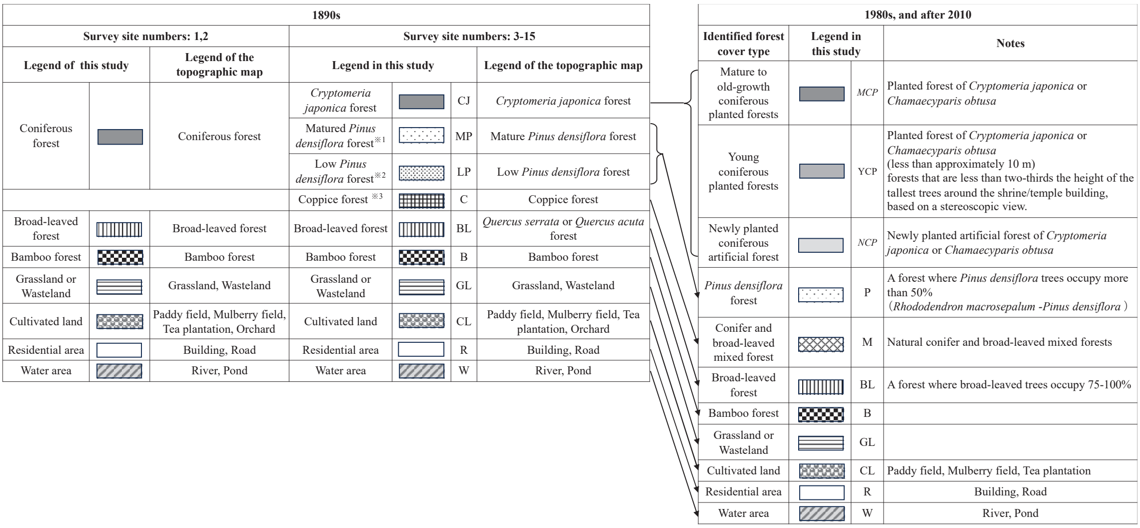

Figure 3. Correspondence of legend for topographic maps and forest cover type identified from aerial photographs. ※1: Mature *Pinus densiflora* forest: A forest primarily consisting of *Pinus densiflora* with a height of approximately 5.4 m or more, and that may also include other tree species [22]. ※2: Low *Pinus densiflora* forest: A forest primarily consisting of *Pinus densiflora* with a height of approximately less than 2.7 m, and that may also include some bare ground [22]. ※3: Coppice forest: A mixed forest consisting of coppices with a height of approximately 1.8 m [22].

Regarding cultural values, forest environments have been discussed within the context of cultural landscape heritage conservation [53,54] or evaluation of sacred natural sites, such as the Delos Initiative [55,56]. In 2021, the International Union for Conservation of Nature and Natural Resources (IUCN) developed guidance on the conservation and management of sacred natural sites from the perspective of both cultural values and ecological values [56]. In these contexts, cultural value refers to the significance that individuals or groups attribute to the forest, encompassing historical, aesthetic, economic, social, scientific, and various other types of value [54,56]. Importantly, the elements and significance that comprise cultural value can change over time, depending on the regional and temporal context [56,57]. This stipulates that cultural values encompass diverse and complex significance accumulated over time. Therefore, the assessment of cultural value requires reassessing the values inherited from previous generations in a contemporary context using a historical approach [57].

Through the following two procedures, the historical forest dynamics of shrine/temple forests from the 1890s to the present (after 2010) were elucidated, and an assessment of the cultural value of shrine/temple forests was conducted. Firstly, using the tabulated area function of ArcGIS, a cross-tabulation of forest cover changes was conducted to clarify the forest dynamics. Other research similar to this study also used topographic maps created in the 1890s and aerial photographs to validate the forest dynamics, and considered changes of 1 ha or more to be significant changes [58]. Therefore, in this study, changes of 1 ha or more were regarded as significant. Secondly, as part of the assessment of cultural value, hierarchical cluster analysis using the *Ward Method* was conducted to understand the trends in forest cover types for each shrine/temple forest in the 1890s. The forest cover types and their functional categorization using the data collected were classified into three categories based on the forest classifications obtained from the topographic maps and previous studies on the landscapes of shrine/temple forests during the 1890s. A designated definition of cultural value for each forest cover type allocated three functional categories according to the IUCN's guideline [56] and the original meaning of shrine/temple forests' existence [9,10] mentioned earlier in the study. The history of the cultural values of shrine/temple forests was explored by tracing the changes in the forest cover type of the three functional categories. The study examined which forest cover type matched the cultural value of each functional category, and how such cultural values transformed due to changes in the forest cover type.

(i) *Landscape forest*

We defined the forests dominated by "mature *Pinus densiflora* forests" or "coniferous forests such as *Cryptomeria japonica*" in the 1890s as landscape forests. The "mature *Pinus densiflora* forest" and "coniferous forests such as *Cryptomeria japonica*" were identified as landscape elements owing to their support of the solemnity of shrines and temples in the 1890s [22,23]. Furthermore, these tree species have timber production functions and were utilized as construction materials for shrine/temple buildings and as general timber. This finding suggests that, along with their landscaping function, these forests also encompassed timber production functions. Hence, the term landscape forest in this study can be regarded as also having timber production functions. The cultural value of landscape forests can be defined as their ability to support the solemnity of shrines and temples and simultaneously provide construction materials for the management of shrines and temples. This includes the knowledge of landscape forestry that enables timber production while maintaining the religious solemnity of shrine/temple forests.

(ii) *Fuelwood forest*

Forests dominated by "low *Pinus densiflora* forests", coppice forests and broad-leaved forests were classified as fuelwood forests. "Coppice forests" are known as fuelwood forests based on the investigation of the "Kyoto Prefecture Geography" and photographs [22]. Moreover, "low *Pinus densiflora* forests" are considered to have grown on land that was extensively logged during the 1870s, based on an investigation of their age [23,51]. These types of forests are known to have been formed due to the high demand for forest resources, primarily firewood and charcoal [51,59]. Additionally, "broad-leaved forests", correspond to the legend "*Quercus serrata* or *Quercus acuta* forest" on the topographical map (1/20,000, surveyed in 1889). It is known for its use as firewood and charcoal. The cultural value of fuelwood forests can be defined as their ability to provide a sustainable supply of firewood and charcoal materials for supporting the livelihoods of people associated with shrines and temples. This includes the knowledge and practice of routine forest maintenance by those community members.

(iii) *Mixed function forest (landscape and fuelwood)*

Forests that possess characteristics of both landscape forests and fuelwood forests were classified as mixed-function forests (landscape and fuelwood). These forests were composed of "mature *Pinus densiflora* forests" and "coniferous forests such as *Cryptomeria japonica*", which represent landscape forests. In addition, they were composed of "low *Pinus densiflora* forests", "coppice forests" and "broad-leaved forests", which represent fuelwood forests. The cultural value of mixed-function forests can be defined as their ability to support the solemnity of shrines and temples, as well as accommodate the production of timber, fuelwood, and charcoal materials. Therefore, these forests support the operation of shrines and temples while simultaneously supporting the livelihood of people associated with shrines and temples. This includes knowledge regarding the selection of suitable locations for each function, and the skills and techniques required to maintain all functions at the same time.

3. Results

3.1. The Historical Forest Dynamics of Shrine/Temple Forests from the 1890s to the Present (after 2010)

3.1.1. The Changes in Each Forest Cover Type from the 1890s to 1980s

Regarding overall change, there was a shift to conifer afforestation, broadleaf tree dominance, and mixed-forest formation within the forest cover types (Figures 4 and 5). Pinus densiflora forests, by the 1980s, were reduced to only 30–40% of their presence in the 1890s. Approximately 30% of the remaining forest cover types were transformed into coniferous planted forests, and around 40% transitioned into broad-leaved or mixed forests. Comparing the trends in change with the buffer areas, it was found that the afforestation of coniferous trees progressed in the early stages, particularly in the areas that were formerly used for fuelwood production (LP, C, BL), as well as grasslands or wastelands (GL). In terms of conifer afforestation, only about 30% of the forests that were Cryptomeria japonica forests in the 1890s remained as mature planted conifer forests, with approximately 40% transitioning into mixed forests. On the other hand, about 30% of the forests that were Cryptomeria japonica forests in the 1890s were converted to young coniferous planted forests or newly coniferous planted forests, with logging and replanting carried out until the 1980s. In former coppice forests, approximately 50% had been transitioned into coniferous planted forests, with half of them being young coniferous planted forests or newly coniferous planted forests. In this context, silvicultural practices involving logging and replanting were carried out until around the 1980s.

3.1.2. The Changes in Each Forest Cover Type from 1980s to the Present (after 2010)

There has been an observed growth in coniferous planted forests, the conversion of Pinus densiflora forests into broad-leaved forests and the conversion of grasslands into coniferous planted forests or broad-leaved forests (Figures 4 and 5). However, significant changes in forest cover types were rarely observed.

3.2. The Forest Cover Types and Their Functional Categories

3.2.1. Forest Cover in the 1890s

Regarding the proportional area for each forest cover within the target shrine/temple forests, we conducted a hierarchical cluster analysis using the Ward Method, resulting in the following five cluster classifications (Figure 6):

- Cluster-1 (1890): Forest dominated by coppice forests, occupying more than 50% of the forested area.
- Cluster-2 (1890s): Forest dominated by coniferous forests such as *Cryptomeria japonica*, occupying approximately 80% of the forested area.
- Cluster-3 (1890s): Forest dominated by broad-leaved forests, occupying approximately 40% of the forested area.
- Cluster-4 (1890s): Forest dominated by low *Pinus densiflora* forests with a height of less than 2.7 m, occupying approximately 80% of the forested area.
- Cluster-5 (1890s): Forest dominated by mature *Pinus densiflora* forests with a height of 5.4 m or more, occupying more than 40% of the forested area.

Among these, Cluster-1 (1890s) and Cluster-4 (1890s) were characterized by an area of approximately 80% or more being occupied by low vegetation, such as low Pinus densiflora forests and coppice forests (No. 14 represents the combined area of low Pinus densiflora forests and coppice forests). A total of seven shrine/temple forests were classified into these two clusters. On the other hand, Cluster-2 (1890s) and Cluster-5 (1890s) were characterized by mature Pinus densiflora forests and coniferous forests such as Cryptomeria japonica, respectively. Each cluster contains three shrine/temple forests, with a total of six shrine/temple forests classified into these two clusters. Cluster-3 (1890s) was characterized by broad-leaved forests. Two temple forests were classified into this cluster. Furthermore, among the shrine/temple forests classified into Cluster-1 (1890s) and Cluster-4 (1890s), the relatively large shrine/temple forests (20 ha or more) showed a significant proportion of mature Pinus densiflora forests or coniferous forests such as Cryptomeria japonica, as seen in No. 10 and No. 13. Similarly, even in Cluster-3 (1890s), the large temple forests, such as No. 3 and No. 12, exhibited a similar trend.

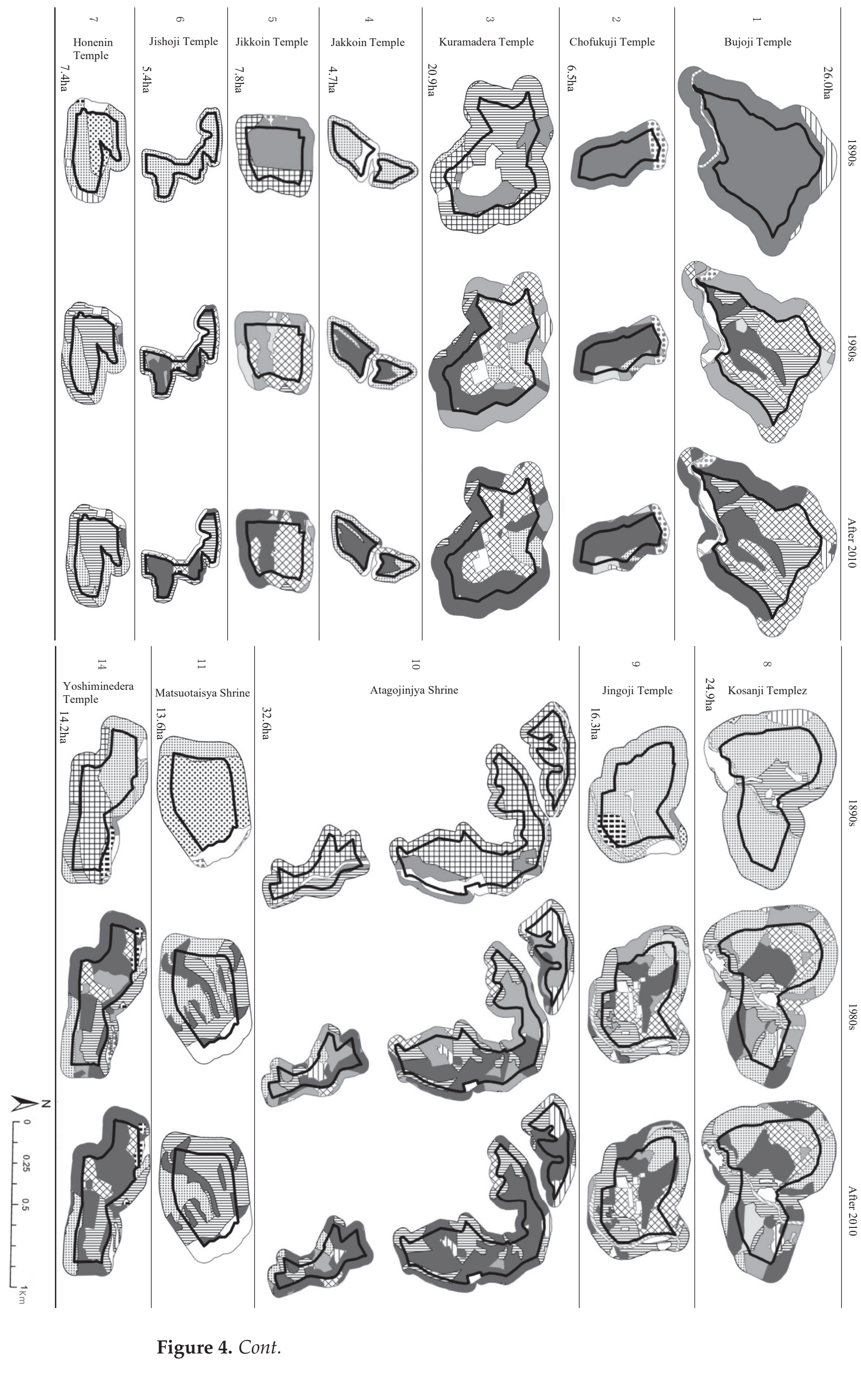

Figure 4. *Cont.*

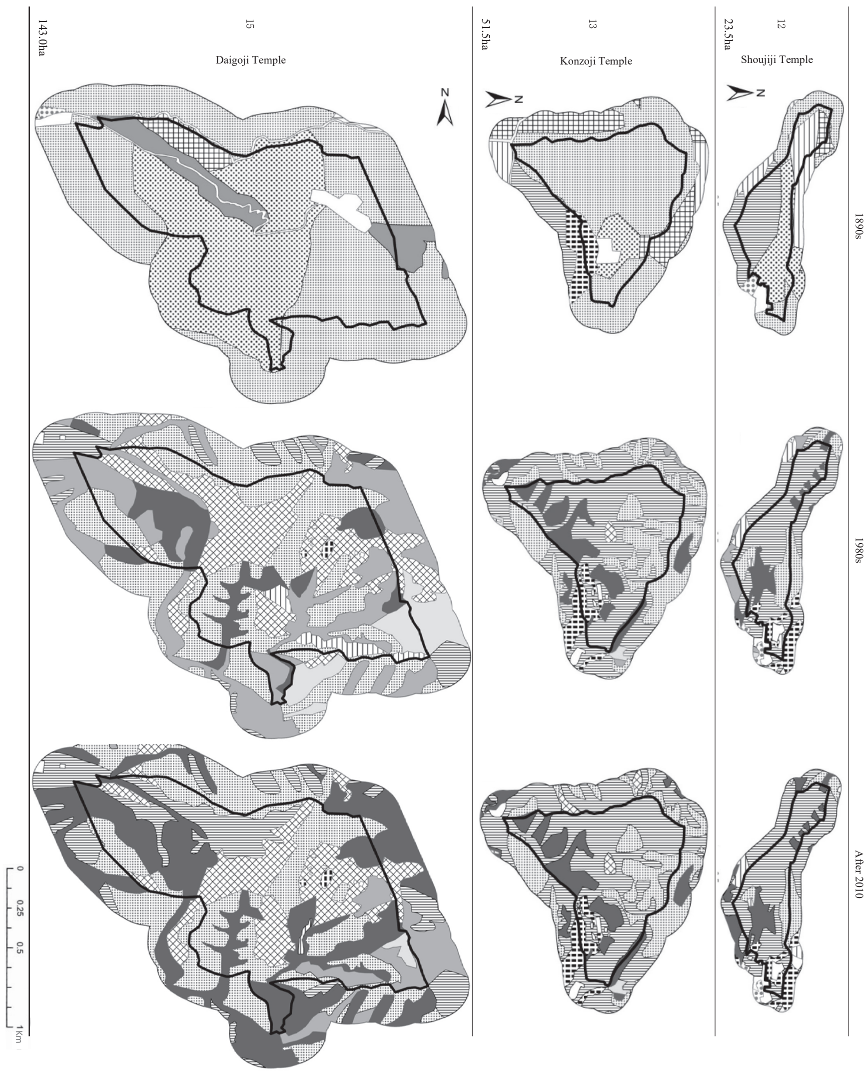

Figure 4. Vegetation maps of 15 shrine/temple forests for each period. Legend refers to Figure 3. The area within the thick border represents A: shrine/temple forest, while the area outside the thick border represents B: buffer.

In the 1890s, shrine/temple forests were classified into different structures, each with its main forest cover types: Coniferous forests such as Cryptomeria japonica (Cluster-2 (1890s)), mature Pinus densiflora forests (Cluster-5 (1890s)), low-vegetation forests, including low Pinus densiflora forests and coppice forests (Cluster-1 (1890s), Cluster-4 (1890s)), and broad-leaved forests (Cluster-3 (1890s)). In the shrine/temple forests dominated by mature Pinus densiflora and coniferous forests such as Cryptomeria japonica (Cluster-2 (1890s), Cluster-5 (1890s)), as well as the larger shrine and temple forests (20 ha or more; Cluster-3 (1890s), No. 10, No. 13), there were noticeable differences in forest structure compared to the surrounding areas (buffer), mainly based on the proportion of mature Pinus densiflora and coniferous forests such as Cryptomeria japonica. On the other hand, the shrine/temple forests classified into Cluster-1 (1890s) and Cluster-4 (1890s), primarily dominated by low vegetation such as low Pinus densiflora forests and coppices forests, did not exhibit clear differences in forest cover when compared to the surrounding areas (buffer).

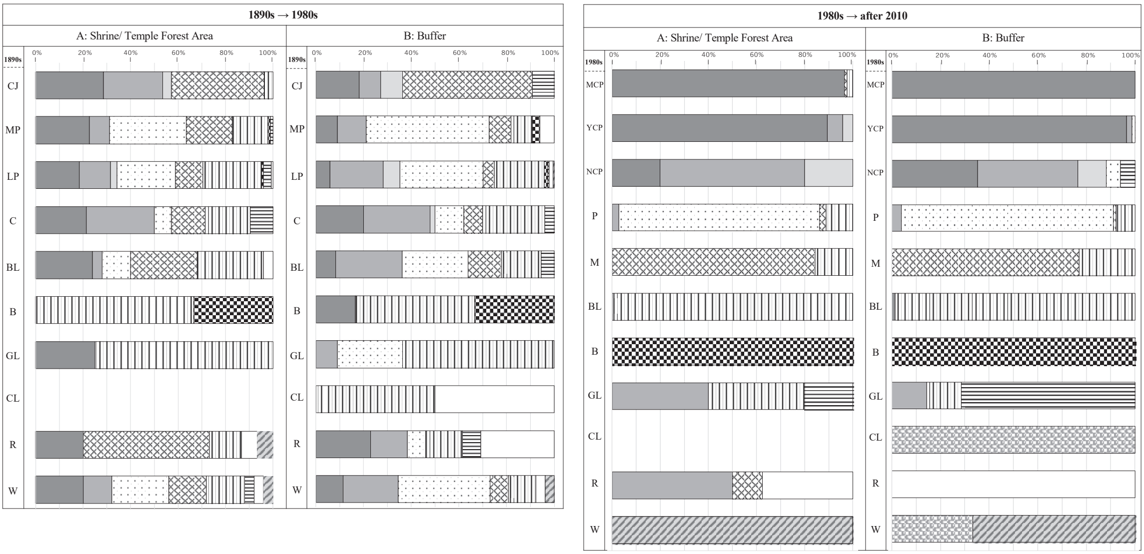

Figure 5. Changes in each forest cover type from 1890s to 1980s and from 1980s to after 2010 for the entire 15 shrine/temple forests. Legend refers to Figure 3. A: Changes in each forest cover type for the entire 15 shrine/temple forests, B: Changes in each forest cover type for the entire buffer area. The change from 1890s to 1980s does not include site No. 1 and No. 2.

Based on the above, these clusters were classified into the following functional categories:

(1) Landscape forests; Cluster-2 (1890s), Cluster-5 (1890s).
(2) Fuelwood forests; Cluster-1 (1890s), Cluster-4 (1890s).
(3) Mixed-function forests (landscape and fuelwood); Cluster-3 (1890s).

3.2.2. Forest Cover in the 1980s

Similar to the previous section, a hierarchical cluster analysis was conducted, and the results classified the data into the following three clusters (Figure 6):

- Cluster-1 (1980s): Forest dominated by *Pinus densiflora* forests or broad-leaved forests, occupying more than 70% of the forested area.
- Cluster-2 (1980s): Forest dominated by mature to old-growth planted coniferous forests, occupying more than 70% of the forested area.
- Cluster-3 (1980s): Forest dominated by young and newly planted coniferous forests, occupying approximately 30% or more but less than 70% of the forested area.

From the composition of the forest cover type, Cluster-1 (1980s) is considered to retain characteristics from both Cluster-3 (1890s), which is dominated by broad-leaved forests, and Cluster-5 (1890s), which is dominated by mature Pinus densiflora forests. Similarly, Cluster-3 (1980s) is thought to retain characteristics from Cluster-2 (1890s), which is dominated by coniferous forests such as Cryptomeria japonica. However, shrine/temple forests that shared similar forest cover and functions in the 1890s exhibited distinct characteristics in their forest cover by the 1980s. In the forest cover of the 1980s, the clusters were primarily formed based on the proportion of planted coniferous forests. The landscape forests, which were dominated by mature Pinus densiflora forests, and the fuelwood forests had disappeared before the 1980s. Among the landscape forests, No. 15 deviated from the characteristics of Cluster-1 (1980s), showing an increase in the proportion of planted coniferous forests and mixed forests. Furthermore, apart from No. 13, the areas classified into fuelwood forests were dominated by low vegetation, such as low Pinus densiflora forests, and areas occupied by coppice forests in the 1890s had more than 30% to 70% of the forested area occupied by planted coniferous forests in the 1980s.

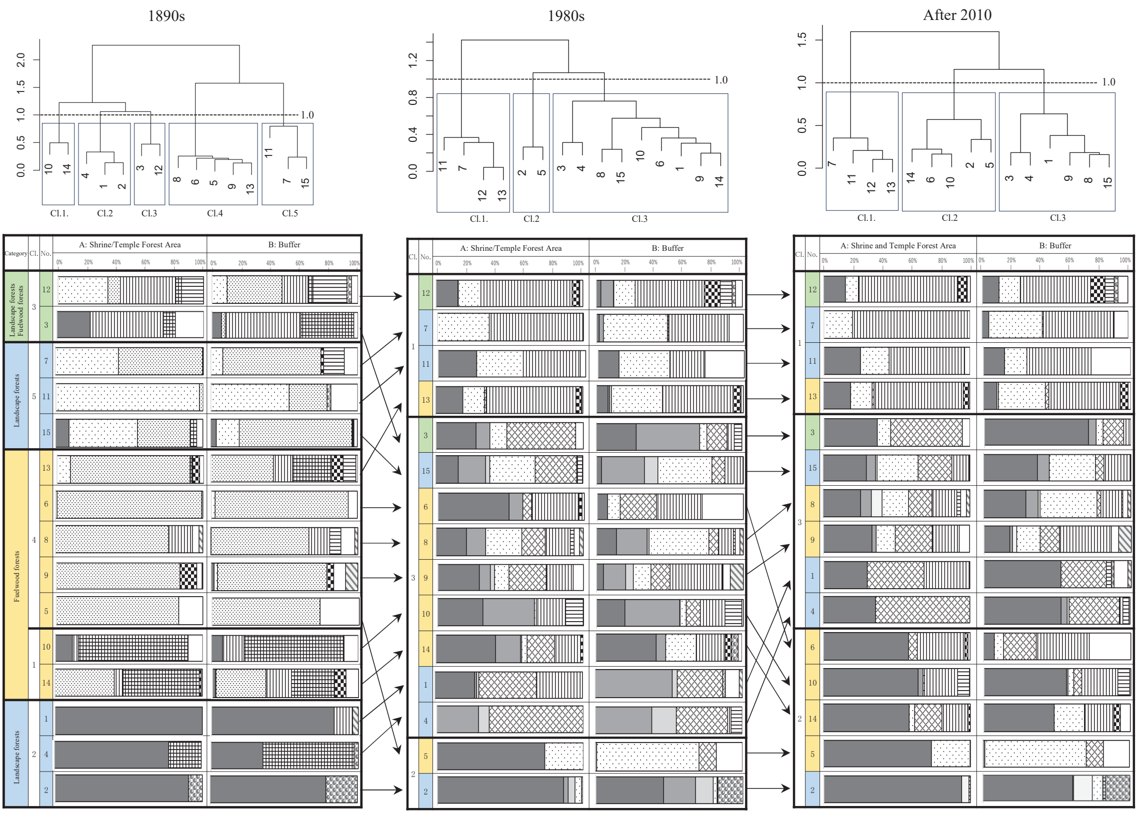

Figure 6. Proportions of forest covers and clusters for each period in each shrine/temple forest. Legend refers to Figure 3. The order of the shrine/temple forests has been adjusted, as appropriate, to facilitate the tracking of the changes in forest cover.

In the 1890s, there were no noticeable differences in forest cover between the shrine/temple forests and the surrounding areas (buffer). However, in the 1980s, many of these shrine/temple forests showed differences with the surrounding forest cover. This is mainly attributed to the proportion of mature to old-growth planted coniferous forests (No. 5, No. 6, No. 8, No. 9, No. 10 and No. 13). The shrine/temple forests classified into Cluster-3 (1980s) exhibited the presence of young planted coniferous forests, so replanting was conducted within the shrine/temple forests. However, the proportion of these young planted coniferous forests did not necessarily follow the forest cover observed in the 1890s, or the shrine/temple forest area trends. Instead, it was likely that the proportions were determined based on the individual policies of each shrine and temple.

3.2.3. Forest Cover after 2010

In the same manner as the previous section, a hierarchical cluster analysis was conducted, and the results classified the data into the following three clusters (Figure 6):

- Cluster-1 (After 2010): Forest dominated by *Pinus densiflora* forests or broad-leaved forests, occupying more than 70% of the forested area.

- Cluster-2 (After 2010): Forest dominated by mature to old-growth planted coniferous forests, occupying more than 50% of the forested area.
- Cluster-3 (After 2010): Forest dominated by mature to old-growth planted coniferous forests or young planted coniferous forests, occupying approximately 30% or more but less than 50% of the forested area.

After 2010, the forest cover clusters were classified in a similar way to those in the 1980s. Cluster-1 (After 2010) consisted of the same temples as Cluster-1 (1980s), and the change in forest cover indicated a transformation from *Pinus densiflora* forests to broad-leaved forests. Furthermore, Cluster-2 (After 2010) included not only the shrine/temple forests classified into Cluster-2 (1980s), but also some of the shrine/temple forests from Cluster-3 (1980s). All of these, except for No. 2, were classified into fuelwood forests in the 1890s, which were dominated by low vegetation such as low *Pinus densiflora* forests and coppice forests. Cluster-3 (After 2010) had the same composition as Cluster-3 (1980s) (No. 1, No. 3, No. 4, No. 8, No. 9 and No. 15), indicating a change in forest cover characterized by the aging of planted coniferous forests. Young planted coniferous forests were observed only in Cluster-2 (After 2010) or some parts of Cluster-3 (After 2010) (No. 2, No. 8, No. 9, No. 10 and No. 15). This indicates that planted forest management involving logging and replanting is rarely being conducted in these areas.

In the 1980s, many shrine/temple forests showed significant differences with the surrounding forest cover, mainly due to the proportion of mature to old-growth planted coniferous forests. However, in the forest cover after 2010, the aging of planted coniferous forests is evident in the shrine/temple forests and the surrounding areas (buffer). Additionally, young planted coniferous forests are limited to very few locations. As a result, except for these few exceptions (No. 5 and No. 6), there are no significant differences between the shrine/temple forest cover and the surrounding areas (buffer)'s forest cover.

4. Discussion

4.1. The Historical Forest Dynamics of Shrine/Temple Forests in Kyoto City

An overview of the forest dynamics in shrine/temple forests during the study periods (from the 1890s to the 1980s, and from the 1980s to after 2010) reveals significant changes from the 1890s to the 1980s. Changes include the afforestation of conifer trees; *Cryptomeria japonica* or *Chamaecyparis obtusa* in the early stages, especially in former fuelwood forests; and the transformation of *Cryptomeria japonica* forests and *Pinus densiflora* forests into broad-leaved forests or mixed forests. On the other hand, from the 1980s to after 2010, there were some instances of silvicultural practices involving the logging and replanting of planted coniferous forests. However, these practices were observed in only about 30% of the entire planted coniferous forests in shrine/temple forests. The predominant changes during this period were natural transitions, such as the growth of planted coniferous forests and the transformation of *Pinus densiflora* forests into broad-leaved forests when affected by pine wilt disease.

In this section, an analysis of the background factors that led to afforestation in former fuelwood forests from the 1890s to the 1980s is presented as follows:

One of the selection criteria for the Kyoto Prefectural Shrine/Temple Forests Survey is a forest age of 75 years and older. It can be assumed that many of the mature to old-growth planted coniferous forests observed in the 1980s were planted between 1868 and 1926 (Japanese Meiji and Taisho periods). In the shrine/temple forests near the urban areas of Kyoto city, rampant logging occurred in the 1870s, whereby shrine/temples tried to sell timbers to generate income before the government's nationalization of their lands [23]. Regarding these areas affected by rampant logging, large-scale afforestation, mainly consisting of *Cryptomeria japonica* and *Chamaecyparis obtusa*, was carried out by the national government from 1884 to 1892 [59] (Annotation A5 in Appendix A). According to Nakajima (1996) [23], during this period, there was a shift in the management policy of national forests in the Kyoto prefecture. Specifically, in 1886, the management of national forests in the Kyoto prefecture was transferred from the Kyoto Prefectural Government to the Ministry of

Agriculture and Commerce. After this transfer, the management policy of national forests shifted from "preserving and restoring scenic beauty" to "conserving the national territory and increasing forest products". As a result, the landscape conservation practices that had been carried out in the Kyoto prefecture for many years were largely disregarded, and a standardized management approach was implemented by the national government. Between the 1890s and 1920s, there were significant developments regarding the ownership and management of shrine/temple forests. Various laws were enacted, such as the National Forest Act of 1899. These laws resulted in the return of the ownership and management of certain forested areas to shrines and temples [60,61]. Additionally, the Forest Act was revised in 1907 to establish the forest planning system, which allowed shrines and temples to engage in forestry management on the returned forested lands. This policy marked a recognition of the rights of shrines and temples to manage and utilize their own forest resources for forestry activities. During the same period, in 1909, the Kyoto Prefectural government issued a directive on planting in shrine grounds and the management of shrine forests (issued by the Ministry of Home Affairs, document number 629) [62]. This directive aimed to encourage forestry management through afforestation in shrine forests, implying that many of the planted coniferous forests established around shrines and temples between the 1890s and 1920s were likely created by either the government or shrines and temples, with the intention of conserving their owned lands and producing timber.

4.2. The History of the Cultural Values of Shrine/Temple Forests

Considering the forest dynamics and the results of the cluster analysis, an examination of the history of the cultural values of shrine/temple forests is conducted as follows.

4.2.1. The Cultural Value of Landscape Forests

As mentioned above, the cultural value of landscape forests is defined as their ability to support the solemnity of shrines and temples while simultaneously providing construction materials for the management of shrines and temples.

Summarizing the changes in landscape forests, the majority of landscape forests existent in the 1890s had disappeared by the 1980s due to the expansion of broad-leaved forests caused by pine wilt disease. Since 2010, semi-natural forests, such as broad-leaved forests or conifer and broad-leaved mixed forests, have become predominant, assuming a landscaping function (except for No. 2). Culturally valuable landscape forests previously supported by mature *Pinus densiflora forests* and coniferous forests have shifted to become semi-natural forests and mainly broad-leaf forests. This implies that the functions encompassed within the cultural value of landscape forests have shifted without prioritizing the timber production function that traditionally coexisted. If the current policies continue to only support natural or semi-natural forest restoration and landscape conservation, the timber production function of landscape forests will be lost. This will result in a further loss of traditional knowledge regarding landscape forestry that enables timber production while maintaining the religious solemnity of shrine/temple forests.

4.2.2. The Cultural Value of Fuelwood Forests

As mentioned earlier in the study, the cultural value of fuelwood forests is defined as their ability to provide a sustainable supply of firewood and charcoal materials for supporting the livelihoods of people associated with shrines and temples.

Approximately half of shrine/temple forests were classified as fuelwood forests in the 1890s. However, many of the fuelwood forests had undergone significant transformations by the 1980s, transitioning into planted coniferous forests or semi-natural forests such as broad-leaf forests or conifer and broad-leaf mixed forests. This indicated that, by the 1980s, the cultural value of fuelwood forests had disappeared compared to the value of fuelwood forests in the 1890s. There was a conversion to semi-natural forests that resulted in a functional shift from the fuelwood production function into landscaping function. This shift contributed to a land conservation function and timber production function within the planted coniferous forests. The shift in the function of the forests in the 1980s implies the multi-layered cultural value of landscape forests, land conservation forests, or timber production forests coexisting simultaneously within the 1890s culturally valued fuelwood forest. However, after 2010, intentional forest management for the timber production function was not efficiently maintained. The continued absence of management indicates that the multi-layered cultural values of these forests since the 1980s will not be renewed. Consequently, this will lead to the homogenization of the cultural characteristics of shrine/temple forests in the long term. Such homogenization of shrine/temple forests will affect the opportunities associated with cultural traditional practices like fuelwood collection and will regenerate the unique forest landscape shaped by these traditional practices related to forest resource use.

4.2.3. The Cultural Value of Mixed-Function Forests (Landscape and Fuelwood)

The cultural value of mixed-function forests is defined as the their ability to support the solemnity of shrines and temples, as well as accommodate the production of timber, fuelwood, and charcoal materials. In the collected data, larger shrine/temple forests (20 ha or more) are classified into this category. The trends observed in forest cover changes up until 2010 in this category were similar to the two categories mentioned above. The landscaping function was mainly supported by semi-natural forests. The fuelwood production function had disappeared, transforming into the landscaping function, land conservation function, and timber production function.

The cultural value of mixed-function forests varied between shrine/temple forests. Some preserved the characteristics of landscape forests, especially with the existence of *Pinus densiflora*. On the other hand, other shrine/temple forests had a higher proportion of planted coniferous forests, acting as timber production forests, and some maintained both cultural values. The cultural value of mixed-function forests can be described as the value associated with the simultaneous preservation of different functions in different areas within shrine/temple forests. Through zoning and other forest management practices, the mixed function of these forest adds intrinsic value to the forest as more than a natural resource. Maintaining such a cultural practice requires a wealth of knowledge and an understanding of the forest management practices best suited to the mixed-function forest environment. Therefore, if management practices disregard the cultural value of mixed-function forests, traditional knowledge regarding the selection of suitable locations for functional categories of forests, as well as the skills and techniques required to simultaneously maintain such a special forest dynamic, may also be lost with time.

5. Conclusions

In this study, we examined forest cover change in shrine/temple forests and their cultural value in Kyoto city. The comparison between forest cover in the 1890s and in the 1980s revealed two major trends: (i) landscape forests have shifted towards semi-natural forests, and (ii) fuelwood forests have transformed into planted coniferous forests. In the first trend, the analysis of cultural value suggested that the current policies, which only support natural or semi-natural forest restoration and landscape conservation, may lead to the trivialization of the cultural value of landscape forests. As mentioned earlier, a continued lack of forest management and the transition to climax forests will lead to a decrease in biodiversity [36,38,39]. For the conservation of the cultural values of landscape forests, in addition to maintaining semi-natural forests through regular management, reforestation with *Pinus densiflora* or planted conifer forests can contribute to enhancing the cultural value of landscape forests. The second trend indicated that multi-layered cultural value has been formed through the history of forest management, although functional change has occurred. In some of the shrine/temple forests examined in this study, it was found that planted forest management strategies involving logging and replanting were conducted until the 1980s. This implies that within the context of human activities, the management of forest stands shaped by ongoing practices has been consistently carried out. This maintenance, even when the forest has different functions, such is the case with fuelwood forests or timber production forests, signifies the renewal and preservation of layered cultural values even after the Meiji period (1868–1912) in the mountainous and foothill areas of Kyoto city.

Based on the above, the cultural value of planted coniferous forests between the 1890s and 1920s can be observed as being intentionally established for land conservation and timber production. This is particularly in areas that were fuelwood forests in the 1890s. These planted coniferous forests were found to have shaped the distinctive forest cover of shrine/temple forests in later years, indicating that planted coniferous forests within shrine/temple forests have retained their multi-layered cultural value dating back a century. However, it was found that, after 2010, planted forest management strategies within shrine/temple forests have been rarely implemented. This has resulted in the aging of planted coniferous forests that were originally intended for land conservation and timber production. The ongoing lack of management implies that these forests' multi-layered cultural value will not be renewed, potentially leading to the homogenization of cultural characteristics in the long term.

For the shrine/temple forests in Kyoto city, the preservation and regeneration of *Pinus densiflora* forests have been emphasized. Similarly, for the planted coniferous forests without forest management practices, there has been a push towards transitioning these areas to semi-natural forests, with the intended purpose of conserving historical landscapes and enhancing biodiversity [24]. As revealed in this study, the planted coniferous forests formed within shrine/temple forests are not adequately managed. Consequently, these planted forests are being converted into semi-natural forests that require less management, without considering their multi-layered cultural values dating back a century. In this process, after intense thinning, a mixed forest of coniferous and broad-leaved trees will be achieved through natural regeneration [24]. There is a concern that the cultural features formed in interaction with humans have become fragmented, and that tracking those cultural features will be difficult.

This study revealed that the planted coniferous forests in the mountainous and foothill areas of Kyoto city have multi-layered cultural value. The assessment and conservation of the cultural value of planted forests run counter to the global trend of restoring "natural" forests. However, the disregard for cultural characteristics shaped by historical human activities implies that these forests' multi-layered cultural value will not be renewed. While past traditional management strategies continue to influence forest characteristics [4], there is a concern that in the long term, it may lead to the homogenization of the cultural characteristics of each forest. There is also the potential loss of traditional knowledge and techniques that have supported the cultural value of shrine/temple forests. A further detailed examination of individual cases will be required to address the homogenization of cultural characteristics and the loss of traditional knowledge and techniques. However, it must be considered that, in this study, the differences in forest cover between the shrine/temple forests and their buffer area were no longer clear after 2010. There is a risk that the distinctiveness of shrine/temple forests and the characteristics and cultural values formed individually by each shrine/temple may disappear. In the conservation of forests formed in close association with human activities, such as shrine/temple forests, there is a need to understand forest dynamics and evaluate cultural values through a historical approach. Due to the varied size and historical background of each shrine/temple forest, the administration may find it challenging to provide comprehensive guidelines or policies through a historical approach. Based on historical evidence, a bottom-up approach would be more feasible. In this context, individual shrines and temples taking the initiative in zoning their forest for the inheritance of cultural value would be effective, whilst conserving their historical landscapes and biodiversity.

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

Funding: This work was supported by JST SPRING, Grant Number JPMJSP2110.

Data Availability Statement: All the relevant data from this study are available from the corresponding author upon reasonable request. The data are not publicly available due to the sensitivity of the study area, some data cannot be made public.

Acknowledgments: The authors thank Ryo Nukina for his feedback on our survey instrument and results.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Annotation A1. The topographical map surveyed in 1889, with a scale of 1/20,000, is a pioneering modern survey map created by the land survey department of Japan's Army and includes detailed descriptions of vegetation.

Annotation A2. The purpose of this project was to select outstanding shrine/temple forests in the Kyoto Prefecture and grasp the current conditions of those forests. It also aimed to contribute to formulating nature conservation measures for the Kyoto Prefecture in the future.

Annotation A3. Among the target shrines and temples, Bujoji Temple and Chofukuji Temple (Survey Site Numbers 1 and 2) were located outside the mapping range of the topographical map surveyed in 1889, with a scale of 1/20,000. Therefore, for these two temple forests, the topographical map surveyed in 1893, with a scale of 1/20,000, was used instead. The 1889 map was created only for the major cities, while the 1893 map was designed to cover the entire country. Both maps were created by the land survey department of Japan's Army, but the legend used on the maps varied depending on the survey era and the region. As shown in Figure 3, the legend of the 1889 map includes more detailed classifications of vegetation compared to that in the 1893 map.

Annotation A4. Among the target shrines and temples, Bujoji Temple and Chofukuji Temple (Survey Site Numbers 1 and 2) were located outside the photography range of the 2020 National Land Image (color aerial photograph taken by GSI), with a scale of 1/10,000. Therefore, the 2010 National Land Image (color aerial photograph taken by GSI), with a scale of 1/10,000, was used instead.

Annotation A5. Examples, in Mount Kifune's national forest, 300,000 *Cryptomeria japonica* trees and 100,000 *Chamaecyparis obtusa* trees were planted (planting area: 66.1 ha). In Mount Kurama's national forest, 80,000 *Cryptomeria japonica* trees s and 20,000 *Chamaecyparis obtusa* trees were planted (planting area: 16.5 ha). Additionally, in Mount Jodoji Oyama's national forest, 15,000 *Cryptomeria japonica* trees and 5000 *Chamaecyparis obtusa* trees were planted (planting area: 3.3 ha), resulting in a total of approximately 136.9 ha of afforestation (Kyoto Prefectural Mountain and Forest Association, 1909).

References

1. Stanturf, J.A.; Mansourian, S. Forest landscape restoration: State of play. *R. Soc. Open Sci.* **2020**, *7*, 201218. [CrossRef] [PubMed]
2. Agnoletti, M.; Piras, F.; Venturi, M.; Santoro, A. Cultural values and forest dynamics: The Italian forests in the last 150 years. *For. Ecol. Manag.* **2022**, *503*, 119655. [CrossRef]
3. Hua, F.; Bruijnzeel, L.A.; Meli, P.; Martin, P.A.; Zhang, J.; Nakagawa, S.; Miao, X.; Wang, W.; McEvoy, C.; Peña-Arancibia, J.L. The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. *Science* **2022**, *376*, 839–844. [CrossRef] [PubMed]
4. Santoro, A.; Piras, F. Natural Forests or Cultural Forests? Forest Changes within Italian Protected Areas in the Last 85 Years. *Forests* **2023**, *14*, 921. [CrossRef]
5. Costanza, R.; d'Arge, R.; De Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'neill, R.V.; Paruelo, J. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]
6. Ministry of the Environment, Government of Japan. Strategy for an Environmental Nation in the 21st Century. Available online: https://www.env.go.jp/guide/info/21c_ens/21c_strategy_070601.pdf (accessed on 10 November 2023).

7. Takeuchi, K. Rebuilding the relationship between people and nature: The Satoyama Initiative. *Ecol. Res.* **2010**, *25*, 891–897. [CrossRef]
8. Ishii, H.T.; Manabe, T.; Ito, K.; Fujita, N.; Imanishi, A.; Hashimoto, D.; Iwasaki, A. Integrating ecological and cultural values toward conservation and utilization of shrine/temple forests as urban green space in Japanese cities. *Landsc. Ecol. Eng.* **2010**, *6*, 307–315. [CrossRef]
9. The Historical Survey Committee of Forestry Development. *History of the Development of Japanese Forestry: Volume I the Process of Development since the Meiji Era*; Ministry of Agriculture, Forestry and Fisheries, Government of Japan: Tokyo, Japan, 1960. [CrossRef]
10. Yamaguchi, T. *The Meiji Government and Religion*; University of Tokyo Press: Tokyo, Japan, 1999.
11. Miyawaki, A. *Plants and Humans–Balance in the Biological Society*; NHK Publishing: Tokyo, Japan, 1970.
12. Narumi, K.; Kobayashi, S. Landscape Changes in the Woods around Shinto Shrines since the Early Modern Era. *Hist. Geogr.* **2006**, *48*, 1–17.
13. Imanishi, A.; Yoshida, S.; Imanishi, J.; Morimoto, Y. The Vegetative Landscape of Kamomioya Shrine and Resource Utilization Found in the Diary of a Shrine Family from the Latter 17th to 18th Century. *J. Jpn. Inst. Landsc. Archit.* **2008**, *71*, 519–524. [CrossRef]
14. Imanishi, A.; Sonoma, S.; Imanishi, J.; Morimoto, Y. The vegetative landscape of Kamo-wake-ikazuchi Shrine and resource utilization found in historical documents of forest management from the 17th to 18th century. *J. Jpn. Inst. Landsc. Archit.* **2011**, *74*, 463–468. [CrossRef]
15. Mineo, K. Introduction to the Study of Temples/Shrines and Forests: A Comparison with Common Forest. *Jpn. For. Commons Res.* **2020**, *40*, 83–99. [CrossRef]
16. Honda, S. Shaji Fuchirin Ron (Management Theory of Shrine and Temple Forest). *Sanrin* **1912**, *356*, 1–20.
17. Kobayashi, A. Trends in Research on Modern Shinto Shrine Grounds. *J. Agric. Sci. Tokyo Univ. Agric.* **2017**, *61*, 126–136.
18. UNESCO World Heritage Centre. Historic Monuments of Ancient Kyoto (Kyoto, Uji and Otsu Cities)-UNESCO World Heritage Centre. Available online: https://whc.unesco.org/en/list/688/ (accessed on 29 October 2023).
19. Nakajima, S. Current Idea of Landscape Conservation and Forestry in Kyoto in the Early Years of the Showa Era: Landscape and forest in Kyoto. *J. Archit. Plan. Environ. Eng. AIJ* **1994**, *59*, 185–193. [CrossRef]
20. Fukamachi, K.; Oku, H.; Kumagai, Y.; Shimomura, A. Changes in landscape planning and land management in Arashiyama National Forest in Kyoto. *Landsc. Urban Plan.* **2000**, *52*, 73–87. [CrossRef]
21. Tanigawa, R.; Yamaguchi, K.; Kawasaki, M. Higashiyama Mountain Development and Scenic Preservation in Modern Times Cable Car Plans and Preservation Measures referring to License and Construction Application. *J. City Plan. Inst. Jpn.* **2021**, *56*, 403–412. [CrossRef]
22. Ogura, J. Vegetation of the Mountainous Area around Kyoto in the Middle Meiji Era. *J. Jpn. Inst. Landsc. Archit.* **1992**, *55*, 37–42. [CrossRef]
23. Nakajima, S. Forestry and Landscape in Kyoto in the First Half of the Meiji Era: Landscape and Forest in Kyoto. *J. Archit. Plan. Environ. Eng. AIJ* **1996**, *61*, 213–222. [CrossRef]
24. Kyoto City, City Planning Bureau. *Guidelines for Conservation and Restoration of Forest Landscape in Kyoto City*; Kyoto City: Kyoto, Japan, 2016.
25. Kyoto Prefecture. *Shrine and Temple Forests in the Southern Area of Kyoto Prefecture*; Kyoto Prefecture: Kyoto, Japan, 1989; pp. 81–207.
26. Shidei, T.; Sano, S. *Pine Trees and Life*; Meigen Shobo: Tokyo, Japan, 1973.
27. Nara National Research Institute for Cultural Properties. *The Cultural Landscape in Kyoto*; Kyoto City: Kyoto, Japan, 2020; Volume 25.
28. Chuping, W.; Ando, M. Stand structure and dynamics during a 10 year period of pine wilt disease forests in Kyoto City. *J. Jpn. Soc. Reveget. Tech.* **2009**, *35*, 440–447. [CrossRef]
29. Mamiya, Y. Pathology of the pine wilt disease caused by *Bursaphelenchus xylophilus*. *Annu. Rev. Phytopathol.* **1983**, *21*, 201–220. [CrossRef]
30. Wingfield, M.J.; Blanchette, R.A.; Nicholls, T.H. Is the pine wood nematode an important pathogen in the United States? *J. For.* **1984**, *82*, 232–235. [CrossRef]
31. Hirata, A.; Nakamura, K.; Nakao, K.; Kominami, Y.; Tanaka, N.; Ohashi, H.; Takano, K.T.; Takeuchi, W.; Matsui, T. Potential distribution of pine wilt disease under future climate change scenarios. *PLoS ONE* **2017**, *12*, e0182837. [CrossRef]
32. Xu, Q.; Zhang, X.; Li, J.; Ren, J.; Ren, L.; Luo, Y. Pine Wilt Disease in Northeast and Northwest China: A Comprehensive Risk Review. *Forests* **2023**, *14*, 174. [CrossRef]
33. Yoon, S.; Jung, J.-M.; Hwang, J.; Park, Y.; Lee, W.-H. Ensemble evaluation of the spatial distribution of pine wilt disease mediated by insect vectors in South Korea. *For. Ecol. Manag.* **2023**, *529*, 120677. [CrossRef]
34. Fu, C.-H.; Hu, B.-Y.; C TT, H.K.; Hsu, W. Prevention of pine wilt disease by soil injection with fosthiazate. *Taiwan J. For. Sci.* **2012**, *27*, 143–148.
35. Okuda, M.; Minowa, Y.; Takahara, H.; Ogura, J. Range expansion of Castanopsis forests during the last 70 years in the Higashiyama hill area, Kyoto. *Jpn. J. For. Environ.* **2007**, *49*, 19–26. [CrossRef]
36. Hirayama, K.; Yamada, K.; Nishimura, T.; Kawamura, S.; Takahara, H. Changes in Species Composition and Diversity with Respect to the successional Stage of Urban Forest in Kyoto City, Western Japan. *J. Jpn. For.* **2011**, *93*, 21–28. [CrossRef]

37. Hiroki, S. Invasion of Quercus variabilis and Castanopsis cuspidata seedlings into secondary forests on the western slope of Mt. Miroku and adjacent hill in Kasugai City, Aichi Prefecture, Japan. *Veg. Sci.* **2001**, *18*, 31–37. [CrossRef]
38. Ozaki, K.; Ohsawa, M. Successional change of forest pattern along topographical gradients in warm-temperate mixed forests in Mt Kiyosumi, central Japan. *Ecol. Res.* **1995**, *10*, 223–234. [CrossRef]
39. Aiba, S.-i.; Hill, D.A.; Agetsuma, N. Comparison between old-growth stands and secondary stands regenerating after clear-felling in warm-temperate forests of Yakushima, southern Japan. *For. Ecol. Manag.* **2001**, *140*, 163–175. [CrossRef]
40. Council for Kyoto Traditional Forest Culture. *Crisis in the Mountains of Kyoto*; Kyoto City: Kyoto, Japan, 2010.
41. Industry and Tourism Bureau. *Statistical Data on Agriculture and Forestry of Kyoto City in 2020 (Forestry)*; Industry and Tourism Bureau: Kyoto, Japan, 2020.
42. Maruyama, H. A Historical Study on the Scenic Beauty of the Forfeited Shrine and Temple Forests in Kyoto in Meiji Era. *Bull. Kyoto Univ. For.* **1987**, *59*, 233–247.
43. Norimasa Aoyagi, Y.Y. The Role of Disaster Prevention in Temples and Shrines' Forests of Kyoto Shown in the National Forests Act (1899). *Disaster Mitig. Cult. Herit. Hist. Cities* **2015**, *9*, 81–88. [CrossRef]
44. Sakamoto, K.; Kobayashi, T.; Ikeuchi, Z. A Case Study on the Structure of the Stand in the Forest Surrounding Shimogamo Shrine, Kyoto. *J. Jpn. Inst. Landsc. Archit.* **1984**, *48*, 175–180. [CrossRef]
45. Murakami, K.; Morimoto, Y. Landscape Ecological Study on the Woody Plant Species Richness and Its Conservation in Fragmented Forest Patches in Kyoto City Area. *J. Jpn. Soc. Reveget. Tech* **2000**, *25*, 345–350. [CrossRef]
46. Ogura, J. *History of Forests and Grasslands How Has Japan's Vegetation Changed over the Years?* Kokon Shoin: Tokyo, Japan, 2012.
47. Shinya Tanaka, M.S. Analysis of cover changes of broad-leaved forest using aerial photographs and GIS. *Kanto J. For. Res.* **2015**, *66*, 167–170.
48. Zhou, W.; Huang, G.; Pickett, S.T.; Cadenasso, M. 90 years of forest cover change in an urbanizing watershed: Spatial and temporal dynamics. *Landsc. Ecol.* **2011**, *26*, 645–659. [CrossRef]
49. Lydersen, J.M.; Collins, B.M. Change in vegetation patterns over a large forested landscape based on historical and contemporary aerial photography. *Ecosystems* **2018**, *21*, 1348–1363. [CrossRef]
50. Miyata, S.; Ogura, J.; Osumi, K. Forest Recovery Process in the Satoyama Working Landscapes of the Northern Keihanna Hills in the Modern Era. *J. Jpn. For. Soc.* **2022**, *104*, 205–213. [CrossRef]
51. Osaka Regional Forest Office. *Forest Landscape Planning in Higashiyama National Forest*; Osaka Regional Forest Office: Osaka, Japan, 1936.
52. Kyoto Prefecture Department of the Environment Nature and Environmental Conservation Division. *Kyoto Prefecture Natural Environment Inventory 2015*; Kyoto Prefecture: Kyoto, Japan, 2015.
53. De la Torre, M. Values and heritage conservation. *Herit. Soc.* **2013**, *6*, 155–166. [CrossRef]
54. Díaz-Andreu, M. Heritage values and the public. *J. Community Archaeol. Herit.* **2017**, *4*, 2–6. [CrossRef]
55. Davydov, A.N. "Solovetsky green meridian" and SNS "Svyatye roshschi"(sacred groves). *Last Large Intact For. Northwest Russ.* **2009**, *24*, 27.
56. Verschuuren, B.; Mallarach, J.-M.; Bernbaum, E.; Spoon, J.; Brown, S.; Borde, R.; Brown, J.; Calamia, M.; Mitchell, N.J.; Infield, M. *Cultural and Spiritual Significance of Nature: Guidance for Protected and Conserved Area Governance and Management*; IUCN, International Union for Conservation of Nature and Natural Resource: Gland, Switzerland, 2021; Volume 32.
57. Spennemann, D.H. The shifting baseline syndrome and generational amnesia in heritage studies. *Heritage* **2022**, *5*, 2007–2027. [CrossRef]
58. Koarai, M.; Hasegawa, H.; Sugimura, S.; Yoshida, T. Effectiveness of the Method for Detection of Land Cover or Vegetation Change using Time-serial Geographic Information with various accuracy and classification category. Case Study on Tama Hill Area, Tokyo. *Theory Appl. GIS* **2011**, *19*, 1–8. [CrossRef]
59. Kyoto Forestry Association. *History of Forestry in Kyoto*; Kyoto Forestry Association: Kyoto, Japan, 1909.
60. National Property Department, Ministry of Finance, Government of Japan. *Disposal of Shrine and Temple Lands*; National Property Department, Ministry of Finance: Tokyo, Japan, 1954.
61. Fukuda, J. Study on the Temple and Shrine Reserve Forest under the National Forest Management System, Case in the Kyoto District National Forest Office. *J. For. Econ.* **2008**, *61*, 17–28. [CrossRef]
62. Kyoto Prefectural Shinto Priests' Association Kyoto Branch. *Kyoto Prefectural Government Regulations Compilation on Shrines*; Kyoto Prefectural Shinto Priests' Association Kyoto Branch: Kyoto, Japan, 1933; pp. 120–122.

land

Article

Impact of Land Use Changes on Ecosystem Services Supply: A Meta Analysis of the Italian Context

Davide Marino, Antonio Barone, Angelo Marucci, Silvia Pili and Margherita Palmieri *

Department of Biosciences and Territory, University of Molise, 86090 Pesche, Italy; dmarino@unimol.it (D.M.); antonio.barone@unimol.it (A.B.); angelo.marucci@unimol.it (A.M.); silvia.pili@unimol.it (S.P.)
* Correspondence: margherita.palmieri@unimol.it

Abstract: Changes in land use and land cover (LULC) are caused by several factors, including climate change, socio-demographic dynamics, human pressures and urban sprawl. These factors alter the structure and functionality of ecosystems and their capacity to provide ecosystem goods and services to society. The study of LULC changes is important for understanding the dynamics of relationships between environmental, social and economic components and for analyzing the factors affecting natural capital. Including ecosystem services (ES) in spatial planning tools and sectoral policies is useful for improving governance. In this paper, the impact of LULC changes on ES provision has been estimated. To this end, we carried out a literature review (Step 1) to select the biophysical and economic coefficients of ES supply by land cover classes and collect them in a database (Step 2). We subsequently aggregated the economic and biophysical coefficients by macro classes (Step 3) and, using the benefit transfer approach, we estimated the change in the supply of ESs concerning permanence and transition phenomena in Italy from 1990 to 2018 (Step 4). The transition phenomena analysis also allowed us to evaluate the consequences of urbanization and urban green space governance on ES supply. Indeed, these urban green spaces can help reduce risks to people's health and safety and mitigate the effects induced by climate change. In total, approximately 800 coefficients (biophysical and economic) of ESs supplied by Corine Land Cover classes were acquired. The results show a reduction in the annual supply of ecosystem services of EUR 927 million (2022) caused by LULC changes between 1990 and 2018. This research proposes a methodology to improve knowledge of ESs concerning anthropogenic impacts and to support land-use planning policies regarding Agenda 2030 for Sustainable Development Goals.

Keywords: benefit transfer; assessment ecosystem services; land use land cover changes; transition matrix; economic and biophysical coefficients; Italian context

Citation: Marino, D.; Barone, A.; Marucci, A.; Pili, S.; Palmieri, M. Impact of Land Use Changes on Ecosystem Services Supply: A Meta Analysis of the Italian Context. *Land* **2023**, *12*, 2173. https://doi.org/10.3390/land12122173

Academic Editors: Luca Battisti, Fabrizio Aimar and Federico Cuomo

Received: 14 November 2023
Revised: 12 December 2023
Accepted: 14 December 2023
Published: 16 December 2023

1. Introduction

1.1. Background

Changes in land use and land cover (LULC) are the result of human activities that have altered the land surface through various social and economic processes, influencing ecosystem stability and the conservation of biodiversity [1,2]. In the past 300 years, the Earth's biosphere has been transformed from a predominantly wild to an anthropogenic environment [3]. The main cause of this transformation is the land use and land cover change, which, in combination with the indiscriminate use of natural resources, has caused a drastic loss of biodiversity [4–6]. Data published by the global IPBES report in 2019 show that land use and land cover changes are responsible for more than 50 percent of human impacts on terrestrial and freshwater ecosystems [7,8]. Some scientific studies based on the meta-analysis approach [9–13] have examined the relationship between biodiversity loss and changes in land use and land cover. These studies show that land surface transformation linked to intensification and urbanization causes a general decline in species richness, composition and abundance. Changes in land use and land cover affect biodiversity and ecosystems in which the provision of goods and services is essential for human well-being [2,14,15]. Indeed, their supply is strictly linked to ecosystems and land use. For example, forested areas are linked to the provision of regulating services (i.e., climate regulation) while grazing areas are linked to provisioning ESs (i.e., forage production). Therefore, a change in land use and land cover can lead to a change in the provision of goods and services [2,16,17]. Changes in land use and land cover on the one hand and the increasing demand for ESs on the other have highlighted the need to implement governance tools to ensure the environmental, economic, and social benefits provided by natural capital for present and future generations. These governance tools, such as the SEEA-EA Environmental Accounting of Ecosystem Services, support public decision-makers to achieve some of the objectives defined in international and EU natural capital conservation policies and strategies. Hence the necessity to monitor the qualitative and quantitative state of natural capital, to assess the costs and benefits related to its consumption, to integrate the issue of ESs into decision-making processes and improve management (Agenda 2030 for Sustainable Development; Biodiversity Strategy for 2030). Having information on the value of ESs increases knowledge about the state of ecosystems and improves decision-making. The availability of reliable information on the value of ESs can make the contribution of natural areas more visible and quantifiable at the highest decision-making levels [18].

1.2. ES Evaluation Methodologies: A Synthesis

The internationally recognized framework for the correct valuation and management of ESs involves the process of mapping, biophysical quantification and economic valuation [19–22]. Specific methodologies can be used for each step. For example, mapping ES supply is mainly based on land use and land cover and the spatial distribution of biophysical/abiotic resources [23–25]. Or it can be done through qualitative matrices that associate each land use and land cover class (Corine Land Cover) with the qualitative value of potential ES provision [26]. Concerning biophysical quantification, the most appropriate methodology can be chosen according to the ecosystem service to be investigated as well as the temporal and spatial scale. The quantification of ESs can be carried out either through the use of software, such as INVEST, ARIES and SolVES, which are based on changes in land use and land cover, or through the use of indicators. The choice of the method depends on the availability of data and the characteristics of the software, which in some cases is designed to estimate only certain services.

The evaluation of LULC changes on ES supply is a current issue. For example, Schirpke et al., 2021 [27] mapped the change in ES supply at the ecoregions scale in Europe between 2000 and 2018. The analysis of LULC changes is also useful for predicting scenarios to support the public decision-maker in territorial and urban planning [28].

Furthermore, several authors have used transition matrices to evaluate the ES supply variation due to LULC changes [29–35].

Concerning the economic valuation of ES supply, monetary techniques inherent to both traditional valuation and consumer surplus (expressed and detected preferences) are used [36]. The choice of the most appropriate economic technique depends on the biophysical quantification that allows for defining the economic characteristics ((non-)rival and (non-)excludable) of the analyzed ESs [2]. In recent decades, an increasing number of scientific publications have been conducted at different spatial scales [22,37,38] using the benefit transfer technique [39–41]. The objective of the benefit transfer method is to estimate the benefits of ESs by transferring available information (especially values) from studies already completed in another location and/or context [42]. It is used in the valuation of ESs either to avoid expensive data collection or to complete an assessment in a limited timeframe [43,44]. Based on this methodology, to facilitate scientific and political debate, databases have been created that systematically aggregate economic coefficients from studies carried out internationally, for example, the Ecosystem Service Valuation Database (ESDV) [45] and The Environmental Valuation Reference Inventory [46]. While at the

European level, Integrated Natural Capital Accounting (INCA) [47] has been implemented, providing an operational procedure for ES valuation.

1.3. The Issues and Innovation of the Study

Our paper aims to assess the impacts of anthropogenic activities on human well-being by analyzing the change in ES supply (biophysical and economic) concerning land use changes that occurred between 1990 and 2018 in Italy. To this end, biophysical and economic values for ES supply extrapolated from the literature were stored in a database. Subsequently, the data were analyzed to define biophysical and economic unit coefficients for land cover classes and estimate, through benefit transfer, the ES supply value in the years under investigation. Finally, to estimate and further detail the change that occurred in ES supply, we combined economic coefficients with the transition and permanence approach from previous work [48]. This approach is innovative as it combines transition matrices with biophysical and economic ES coefficients for land cover classes.

The study, while having its limitations, is the first step in a line of research that aims to propose approaches to estimate the variation of ESs on spatial and temporal scales. Such studies could support the governance and implementation of natural capital conservation policies and strategies at a global level.

2. Materials and Methods

This research was carried out in four steps, which are shown in Figure 1. After conducting the literature review (Step 1) we selected the biophysical and economic coefficients of ES supply by land-cover class. We created a database, associating each land use and land cover class with a biophysical and economic coefficient (Step 2). Next, we aggregated these values by macro class to increase the degree of coverage of the biophysical and economic coefficients for Corine Land Cover classes (Step 3). Finally, using the benefit-transfer approach, we assessed the variation in ES supply in relation to permanence and transition phenomena [48] in Italy from 1990 to 2018 (Step 4).

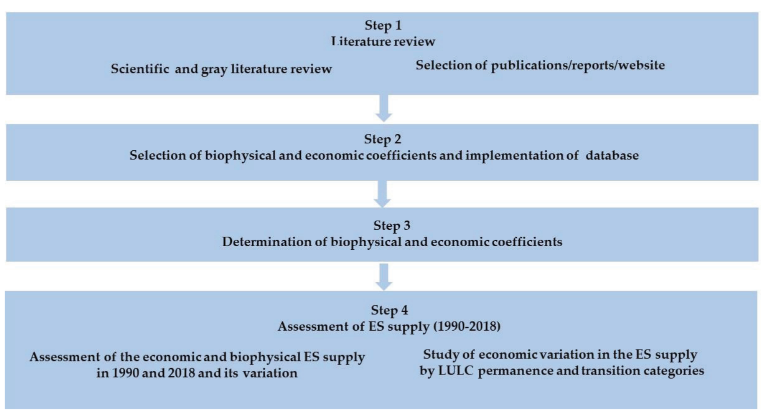

Figure 1. Methodological framework.

2.1. Study Area

The study area corresponds to the territory of Italy, which covers 301,605 square kilometers (Figure 2).

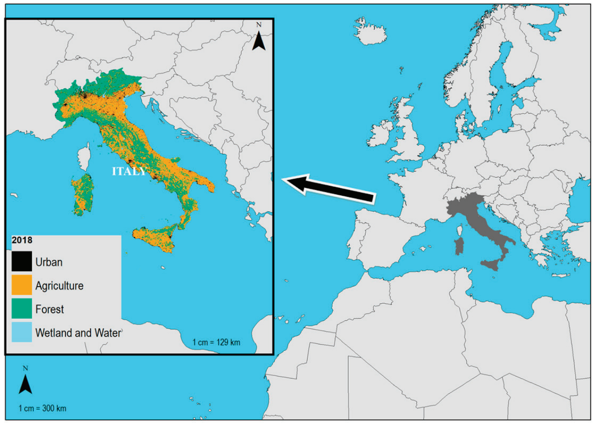

Figure 2. Study area.

The study of land use changes was conducted through the approach of transition categories [48,49] which allows synthesizing the results related to the dynamics of transformation and permanence of land uses (Perm.) into classes such as permanence (of arable land, permanent crops, urban area, forests, heterogeneous agricultural areas, water bodies), evolution to complex systems (Etcs), urbanization (Urb.), agricultural intensification (Ag. Int.) and extensification (Ag. Ext.) and forest expansion (For. Exp.) (Figure 3).

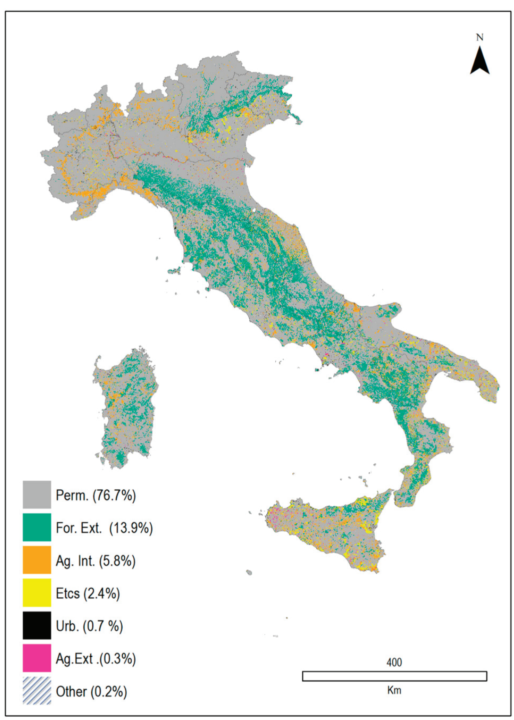

Figure 3. Transition categories areas (%) in Italy (1990–2018). (Ag. Ext.: agricultural extensification, Etcs.: evolution to complex system, Ag. Int.: agricultural intensification, Perm.: permanence, For. Ext.: forest extension, Urb.: urbanization).

The predominant category is permanence, which occupies 77% of the study area. Forest extension covers 14% of the area, agricultural intensification 6%, complex system evolution 3%, and urbanization 1%, while extensification affected close to zero percent of the area. Each transition has shown a specific presence at the regional level: e.g., urbanization is particularly important in the Piemonte region in the north (2880 ha), evolution to complex systems and intensification in Sicily in the south (respectively 174,181 and 624,255 ha).

2.2. Literature Review (Step 1)

The bibliographic review started in March 2023. First, we used the Scopus search engine [50] to analyze the scientific literature over 23 years from 2000 to 2023. We tested different combinations as search queries consisting of the same set of keywords for the title, author keywords and abstract sections. Within the combinations, we used: (i) economic AND biophysical AND value AND ecosystem AND services; (ii) economic AND coefficient AND ecosystem AND services; biophysical AND coefficient AND ecosystem AND services. In addition, we consulted the ESVD database [45]. Despite the quantity of studies available both in the Scopus search engine [50] and in the ESVD database [45], we selected data considering: (i) studies conducted in areas with a similar climatic typology to Italy; (ii) the possibility of associating the ES values with our minimum considered spatial unit, that is, the CLC class at level III; (iii) the availability of coefficients (biophysical and economic) referring to the surface area (e.g., EUR /ha). We also consulted grey literature (Appendix A) and other statistical sources. In particular, for the extraction of the unit coefficients for the agricultural production service, we referred to the agricultural section of the Italian Institute of Statistics (ISTAT) [51] and data from the Research Council for Agriculture and Agricultural Economics Analysis [52]. From the first source, we extracted the biophysical production values per hectare of the major Italian crops, and from the second the respective economic values per Mg produced. Concerning the ESs analyzed in our paper, we have not considered cultural ESs. As regards green urban spaces in Italy, we have selected some articles, including those by Manes et al., 2014 [53] and Bottalico et al., 2016 [54], which highlight their contribution in terms of PM_{10} removal (air purification ES).

An obstacle to research has also been the persistence—despite the fact that the scientific literature seems to converge towards shared nomenclatures (e.g., CICES)—of differentiation both in the ES nomenclature and in assessment approaches.

2.3. Selection of Biophysical and Economic Coefficients and Implementation of the Database (Step 2)

From the studies selected in the literature review, we then extracted the biophysical and economic supply values of ten ESs (four provisioning and six regulating), in the form of unit coefficients per hectare, at CLC level III. We have not considered cultural ES because, in comparison to regulating ESs and provisioning ESs based on biophysical attributes of ecosystems, they are studied through relational and place-based approaches. The provisioning ESs and regulating ESs are often investigated through land cover analysis and remote sensing techniques that associate biophysical values with land uses [55], while cultural ESs are often analyzed through participatory approaches such as, for example, participatory mapping, to reveal place knowledge and related cultural benefits [56,57]. In fact, aesthetic and spiritual recreational benefits are strictly linked to the environmental, cultural and historical heritage of the area.

The biophysical and economic values were entered into a database and sorted by the ES type considered and by the CLC Level III class providing the specific service. Finally, for the economic coefficients, we converted and discounted the estimates into 2022 EUR ha^{-1} yr^{-1} using the consumer price index [58].

2.4. Determination of Biophysical and Economic Coefficients (Step 3)

Since the collection of coefficients at CLC Level III did not allow for optimal coverage of land uses that could potentially generate ESs, we aggregated these values into 'macro classes'. To do this, we used the weighted average based on the proportion in the area (in

1990 and 2018) of the CLC Level III classes contained within the "macro classes". These macro classes conform to the CLC Level II land use classification, except for classes 100 and 500 which are higher-order aggregations (see Section 3.2). We then analyzed the coefficients collected through statistics such as the mean, standard deviation, median, minimum, and maximum for each macro class and each ecosystem service. This allowed us to analyze the distribution of values, their variability and to identify the central values.

2.5. Assessment of ES Supply (1990–2018) (Step 4)

To quantify the supply of services in 1990 and 2018 and the related variation, we used the values for macro classes, and in particular the average values for provisioning services and the median values for regulating services. The choice of using median values for regulating services is because the values (both biophysical and economic) extracted for regulating services have very wide ranges and internal variability, and the median is generally a more appropriate indicator of centrality in the distribution in such cases [59]. The selected values were then multiplied by the area of the specific macro class in 1990 and 2018, resulting in the ecosystem service provision in the two years under investigation. Finally, the relative difference was calculated.

The variation in the ES supply has been more in-depth and summarized through the transition category approach to explain land use change (permanence and transitions) in relation to the specific ES supply variation that occurred in the investigated period.

3. Results

3.1. Literature Review

In total, we considered 29 references that provide biophysical and economic values of ten ES (four provisioning and six regulating ESs) in the function of land cover such as agricultural production, forage production, timber supply, mushroom supply, global climate regulation (carbon sink), air purification, water regulation, water purification, erosion protection and flood risk mitigation.

The studies reviewed (listed in Appendix A) were conducted in Europe (90%), America (7%), and China (3%). From these studies, we extracted about 800 coefficients associated with land cover classes (Corine Land Cover), of which 383 were biophysical and 404 economic. The largest number of coefficients extracted from the analyzed scientific articles concerned the services of global climate regulation, air purification, erosion protection, flood mitigation and raw material supply (timber) (Figure 4).

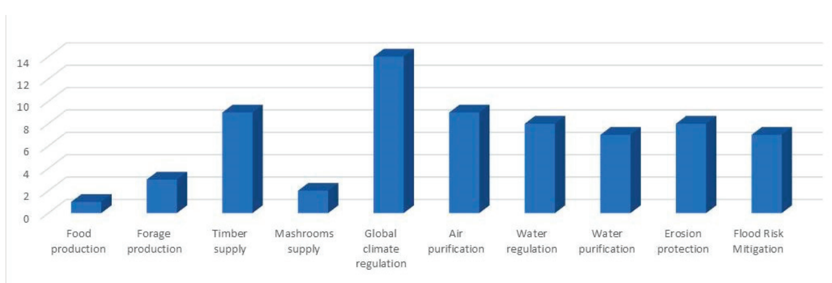

Figure 4. Bibliographic sources used for ES (number).

From analyzing the bibliographic sources, a heterogeneity of methodologies emerged, especially for the quantification and evaluation of regulating ES. Some authors, for example, used the INVEST software for the quantification of erosion protection and flood mitigation ESs [49,60].

The choice of methodologies and software to be used often depends on data availability [61]. Moreover, the economic and biophysical value of an ecosystem service can be calculated by different methodologies. For example, the economic value of the global climate regulation ES can be estimated either by the market price or the social cost method [2,62]. This can lead to unit coefficients of different orders.

The variety of methods and software used for some ESs produces data with a large range of values (MIN and MAX).

Furthermore, it is highlighted that biophysical and economic values are strongly influenced by the spatial context. For example, erosion protection and flood mitigation services are closely related to vegetation cover, geology, lithology, soil gradient, altitude, etc. [63–65]. We also observed that many authors have used the same biophysical and economic coefficients to estimate ESs. For example, the work of Nowak et al., 2006 [66] and Escobedo & Nowak (2009) [67] was used to estimate the air purification service. From the bibliographic review (see Appendix A) we observed that for some classes of land use, there is a lack of biophysical and economic coefficients for the provision of ESs. The reason is dual: (1) the scientific literature is limited; and (2) some land cover classes have no or low potential capacity to provide services as indicated by Burkhard et al., 2014 [26]. In this sense, we have found that in the literature, there is a marked majority of studies on the ecosystem services provided by forests, compared to other ecosystems. This trend in the literature can be attributed to the fact that forests are among the ecosystems with the greatest capacity to provide ecosystem services, both in terms of abundance and variety.

3.2. Determination of Biophysical and Economic Coefficients

Below is a figure (Figure 5) representing the biophysical and economic unit values of the ten ESs analyzed (mean in the case of provisioning ESs and median for regulating ESs, see Sections 2.4 and 2.5 in Section 2). The values are associated with the macro classes of land use and land cover.

LULC macroclass	Food production		Forage production		Timber supply		Mushrooms supply		Global climate regulation	
	Mg/ha/year	€/ha/year	Mg/ha/year	€/ha/year	m^3/ha/year	€/ha/year	kg/ha/year	€/ha/year	$MgCO_2$/ha/year	€/ha/year
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
141	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	10.7
210	7.2	3208.7	1.6	233.9	0.0	0.0	0.0	0.0	1.1	40.5
220	5.6	3332.4	0.0	0.0	0.0	0.0	0.0	0.0	1.7	62.9
230	0.0	0.0	1.8	234.6	0.0	0.0	0.0	0.0	2.3	83.9
240	3.2	1647.4	0.7	101.1	0.0	6.6	0.9	7.2	1.7	62.2
310	0.0	0.0	0.4	51.5	2.4	167.7	1.5	27.1	5.7	196.9
320	0.0	0.0	0.5	67.1	0.0	11.0	0.8	11.4	3.5	127.8
330	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
500	0.0	0.0	0.1	10.1	0.0	0.0	0.0	0.0	0.7	48.7

LULC macroclass	Air purification		Groundwater recharge		Water purification		Erosion protection		Flood mitigation	
	$MgPM_{10}$/ha/year	€/ha/year	m^3/ha/year	€/ha/year	kg N,P/ha/year	€/ha/year	Mg/ha/year	€/ha/year	m^3/ha/year	€/ha/year
100	0.0	0.0	0.0	0.0	0.02	0.05	0.0	0.0	6.0	2.8
141	0.02	19.0	80.0	47.4	1.6	4.7	0.0	0.0	309.7	142.5
210	0.0	0.0	2804.0	1430.0	0.0	0.0	0.0	143.8	298.8	137.5
220	0.0	0.0	0.0	0.0	0.6	1.7	9.1	459.8	537.6	247.3
230	0.0	0.0	1788.5	1423.9	0.0	0.0	4.6	301.6	309.7	142.5
240	0.0	0.0	1570.0	0.0	0.8	2.2	8.6	297.0	309.7	142.5
310	0.3	1433.4	3097.0	91.9	2.8	15.8	16.1	497.0	744.8	334.0
320	0.2	1105.6	1757.4	773.8	2.3	5.3	6.1	520.9	465.2	214.0
330	0.0	0.0	975.1	0.0	0.7	2.2	0.0	0.0	339.7	156.3
500	0.0	1.1	3736.6	16.2	2.0	556.3	0.0	711.0	650.9	1122.9

Figure 5. Biophysical and economic values (EUR 2022) per hectare and LULC macro class used for the quantification of ES. Macro class codes correspond to urban areas (100), urban green areas (141), arable land (210), permanent crops (220), pastures (230), heterogeneous agricultural areas (240), forests (310), shrub and/or herbaceous vegetation (320), non and sparsely vegetated areas (330) wetland and water bodies (500). In water purification ESs the letters N and P stand for nitrogen and phosphorus, respectively.

The weighting by macro classes allowed us to obtain a distribution of the coefficients also for those land cover classes in which data was not available from our bibliographic research.

The values reported thus represent the annual (biophysical and economic) flow of ESs for each land use and land cover macro class.

3.3. ES Supply in the Years Investigated and Their Variation

The application of the coefficients found to the Italian land cover in 1990 and 2018 returned the results summarized in the figures below. In particular, Figure 6 shows the breakdown of the economic value of services in the most recent year, 2018.

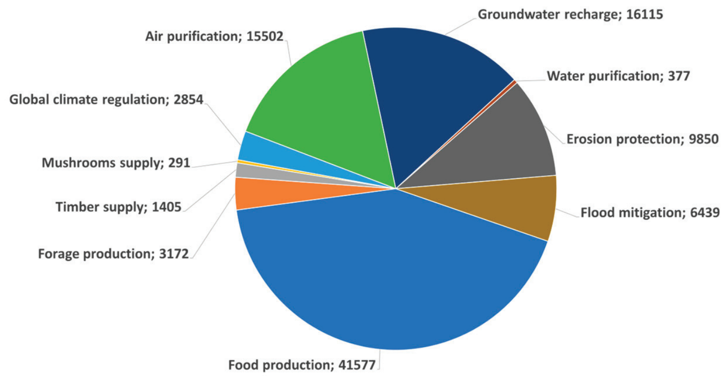

Figure 6. Economic values (in 2022 EUR millions) of the analyzed ES for the year 2018.

It can be seen that the service that obtains the highest economic value is food production with a detected value of about 41.5 billion. This is followed by groundwater recharge (about 16 billion), air purification (about 15.5 billion), erosion protection (about 10 billion) and flood mitigation (about 6.5 billion). Finally, with even lower, but still significant values, we find forage production (about 3 billion), climate regulation (almost 3 billion), and timber supply (about 1.5 billion). Water purification and the supply of undergrowth products, especially mushrooms, close with values in the hundreds of millions. Note that those shown are the values of the annual flows (in 2018) of the ten ESs investigated. The total economic value of annual ES supply flows in 2018 is about 97.5 billion. Regarding the change in the annual flows of ES, Figure 7 shows the economic fluctuation of each ES supply determined by LULC changes over the period 1990–2018.

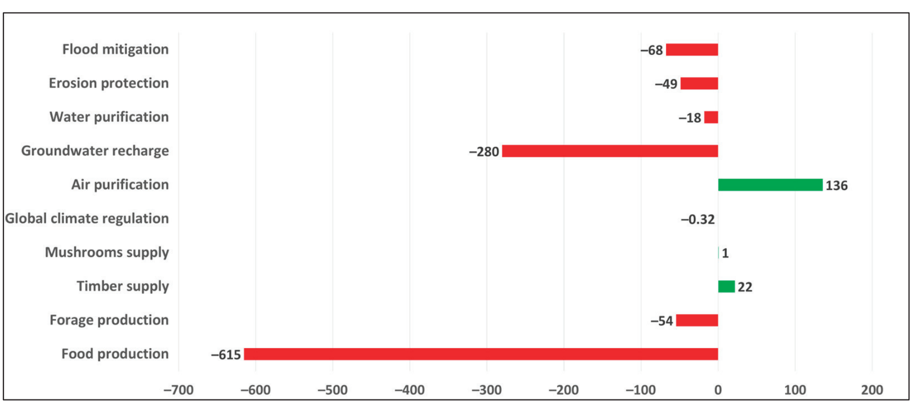

Figure 7. Positive (in green) and negative (in red) economic supply variation (in 2022 EUR millions) of the ten ES considered between 1990 and 2018.

It can be seen that the greatest change in absolute terms is attributable to the agricultural production service, with a loss in annual supply estimated at around 615 million. This is followed by a reduction of about 280 million for the groundwater recharge service. The other services show reductions of an order of magnitude smaller than the first two and concern the ESs of flood mitigation (−68 million), forage production (−54 million), erosion protection (−49 million) and water purification (−18 million). At the same time, for three ESs, we noted an increase in annual supply. In particular, the largest increase is for the ES of air purification with +136 million, followed by relatively smaller increases, i.e., +22 million for timber supply and about +1 million for the supply of mushrooms. We can therefore see that seven out of ten services show negative changes, two of which (agricultural production and groundwater recharge) in the order of hundreds of millions. Overall, the LULC changes in the Italian context that have occurred in the 28 years between the two years investigated, have led to a net reduction in the total annual flow of the considered ESs of EUR 927 million. Finally, the change, expressed in percentage terms, in the biophysical supply of services in 2018 compared to 1990 is shown below (Figure 8). The change in ESs, in this case, has been calculated in percentage terms to obviate the different units used to quantify the different ESs (Mg of CO_2 sequestered, m^3 of runoff avoided, etc.).

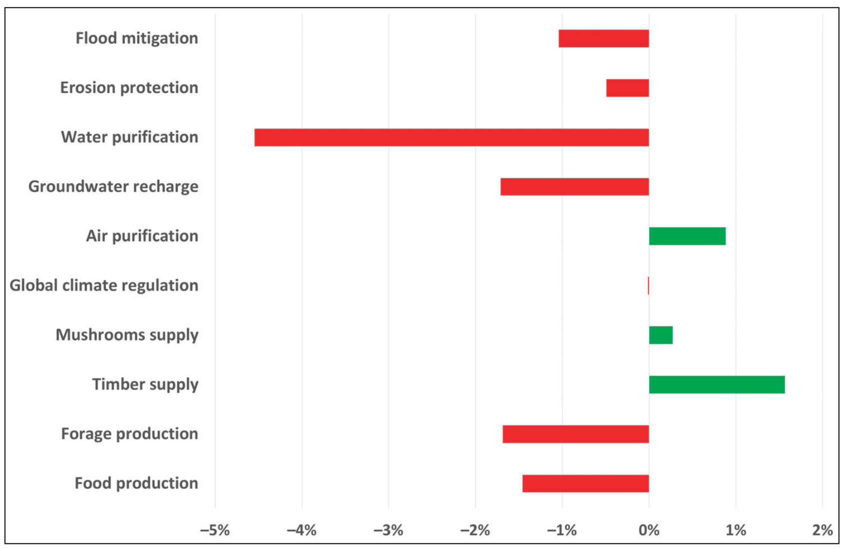

Figure 8. Positive (in green) and negative (in red) Change (%) in the annual biophysical ES supply between 1990 and 2018.

In terms of percentage change, it can be seen that the service that varies the most is water purification, with about +5% (or about +1.9 million kg of pollutants removed) in 2018 compared to 1990. The service that varies the least is that of global climate regulation, with a reduction of only 0.04% (or about 31,000 fewer Mg of CO_2 sequestered). Of the negative changes, the largest is agricultural production, with a reduction of just over 1% (almost 1 million Mg of agricultural products) compared to 1990. In only two cases (water purification and erosion protection) are the changes found to be the opposite of what was found for the respective economic analysis (see Figure 7). This can be attributed both to the different coverage of land uses in terms of biophysical and economic unit coefficients found in the literature, as well as to the values found, which in some cases differ in the magnitude of service provision.

3.4. Economic Variation of ES Supply Concerning the Permanence and Transitions Categories

Concerning the analysis of ES supply variation (Figure 9), the results highlight a relevant economic increase related to the agricultural intensification (+EUR 1677 M) and, conversely, a great decrease linked to evolution to complex system categories (−EUR 1521 M).

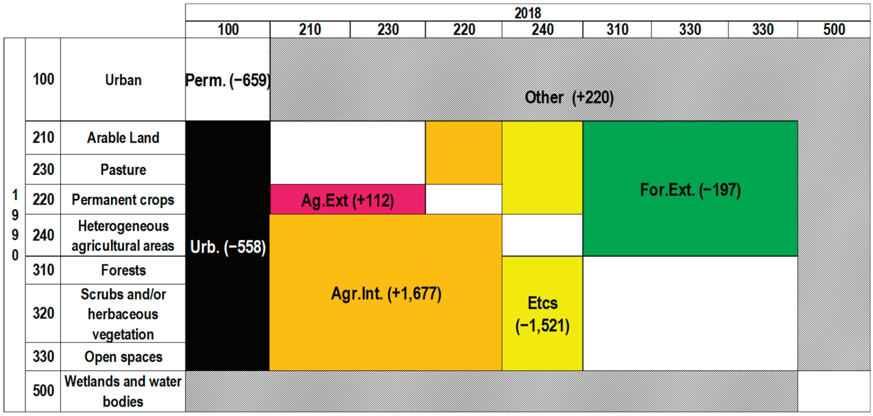

Figure 9. Transition categories and economic variation (EUR millions). Every color corresponds to the label transition category.

In the first case, the increase is due to 77% of the changes toward both arable land (210) and permanent crops (220) from heterogeneous (240) and from forests (310, 320, 330). A low increase, corresponding to 1%, is caused by changes from open spaces with little or no vegetation (330) toward heterogeneous agricultural areas (240).

In the second case, 66% of the transitions toward heterogeneous agricultural areas are caused by changes from arable land (210), 33% are caused by changes from permanent agricultural areas (220), and the rest are caused by changes from forests (310).

Permanence also generates a variation in ESs. This category includes areas in which there are different types of land use permanence such as (i) permanence of permanent crops (olive grove, vineyard, orchard), (ii) permanence of arable land and pastures, (iii) permanence of artificial surfaces and (iv) permanence of heterogeneous agricultural areas. This variation depends on the different coefficient values associated with each land use and the consequent value variation: e.g., in economic terms, the loss of pastures in favor of arable areas gives rise to an increase in food production of more than EUR 3000/ha. For this reason, it is possible to detect ES variations.

Furthermore, since the coefficients for macro classes were obtained on the basis of the values assigned to CLC Level III classes and weighted for the respective macro class areas in 1990 and 2018—the final coefficients for macro classes in 1990 and 2018 do not always coincide. This also allows for the internal variability of the specific macro classes in the two years that were considered and leads to possible variation even in the permanence of the same macro class.

The results of the economic variation analysis are presented in Table 1, summarized for single ESs and single transition categories. Table 1 shows the economic variation of ES supply based on the phenomena of LULC permanence and transition. Between 1990 and 2018, we experienced an economic loss of ESs estimated at EUR 927 million as a result of transition and permanence processes. Evolution into complex systems is the transition that has caused the major loss of ESs (EUR 1521 M). Through evolution to complex systems, productive agricultural systems have been fragmented into different mosaics leading to the loss of all ESs except for the ecosystem service of mushroom production. Evolution to complex systems, permanence, urbanization and forest extension have resulted in an overall loss of agricultural production of EUR 625 million. For example, in rural areas, the abandonment of agricultural areas has favored the growth of forested areas, which has led to an increase in all regulating services and some provisioning services, such as timber and mushrooms. Another relevant result is the high increase in economic value associated with agricultural intensification due to increased food production.

Table 1. Economic variation of ES supply (in 2022 EUR millions) summarized by transition categories.

	Perm.	Urb.	Ag. Ext.	Ag. Int.	For. Ext.	Etcs	Other	Tot
Food	−853	−342	43	1883	−653	−822	129	−615
Fodder	−54	−19	21	40	−29	−22	8	−54
Timber	41	−3	−4	−11	2	−4	1	22
Mushroom	5	−2	−1	−9	2	4	0	1
Global climate regulation	32	−16	−5	−36	20	−1	5	0
Air purification	462	−34	−31	−475	278	−77	12	136
Groundwater recharge	−306	−30	130	373	76	−558	34	−280
Water purification	−14	−2	0	−3	1	0	0	−18
Erosion	41	−73	−29	−90	84	−3	20	−49
Flood mitigation	−13	−38	−12	5	19	−38	11	−68
Tot	−659	−558	112	1677	−197	−1521	220	−927

Conversely, the highest decrease associated with this transition category is linked to air purification.

On the other hand, to explain the major negative variation, the study highlighted that the evolution toward complex systems that occurred between 1990 and 2018 led to a remarkable decrease in economic value because of the great loss in food production and in groundwater recharge. In general terms, the total variation is mainly related to the negative fluctuation of food production and groundwater recharge.

Concerning urbanization processes, it should be noted that these processes are about one percent in area (out of the total of permanence and transitions) and include the increase of green urban areas (+1049 ha) and sports areas (+14,386 ha).

These two subclasses, and in particular, green urban areas (CLC 141), in contrast to the other urban areas (e.g., continuous urban fabric), provide ESs that are in some cases even relevant and certainly fundamental for communities in cities [68,69]. In fact, through a coefficient search, we found that green urban areas generate ESs such as global climate regulation, air purification, groundwater recharge and flood mitigation (see Figure 5). In our review, we found the highest values for the flood mitigation service, with an average economic value of EUR 175 per hectare of green urban area.

To analyze the spatial distribution of the economic variation in the investigated time period, the regional administrative boundaries have been overlaid as shown in Figure 10. Our study demonstrates a certain clustering of value fluctuation. In large areas in the central area of Veneto, (NE), and in Sicily (S), for example, the study highlighted strong decreases of economic value in the order of more than −EUR 800 M. This variation was caused in most of the cases by agricultural land abandonment (Etcs transition category) that determined, in turn, the great loss of food production. In the named regions, the decreases were only in part contrasted by ES increases generated by forest permanence. As far as negative variations are concerned, in the western part of Valle D'Aosta region and in the Piemonte region (NW), it is possible to detect large areas of increases of more than +EUR 100 M. These phenomena are linked to forest permanence and specifically to the transformation from scarce vegetation cover toward higher vegetation abundance.

Zonal statistics applied at the regional variations pointed out that at both average and sum levels, seventeen out of twenty regions have experienced decreases in economic value. Fluctuation was especially negative in Sicily and Veneto while, on the contrary, was strongly positive in Valle d'Aosta.

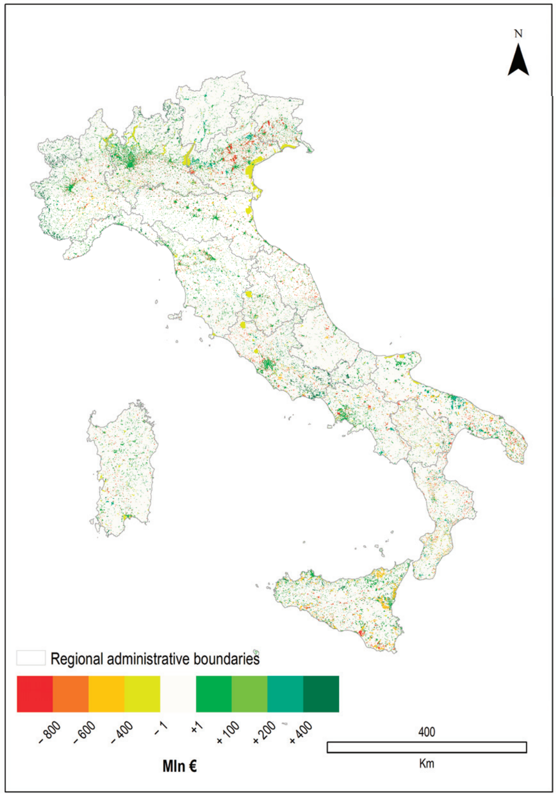

Figure 10. Spatial distribution of economic value variation (M ln EUR).

4. Discussion

This work belongs to the growing body of literature that seeks to estimate the value of natural capital and the impacts of LULC changes on the ESs it provides. Some authors [31,32,34] have used transition matrices to study LULC and landscape changes. For example, Assefa (2012) [30] used these matrices and the coefficients of Kindu et al. (2016) [70] to assess ESs. In many cases, to assess the ES variation at the level of biomes, the coefficients of Costanza et al. (1997, 2014) [21,22] are used. In our study, we have used biophysical and economic coefficients at a spatial scale of greater dictum (Corine) which are thus potentially more useful for studying the processes of permanence and transition. Since ESs are the basis for human well-being and survival, spatial transformations can have very significant impacts on multiple domains of well-being [22,71,72]. The results obtained in this paper can contribute to the international debate on the need to study and understand how LULC changes affect the ES provision [73–76]. For example, while the increase in agricultural areas at the expense of natural and semi-natural environments leads to an increase in agricultural production services, it also leads to a reduction in the provision of other services such as carbon absorption, air purification, etc. The processes of land transformation are also influenced by several factors including socio-demographic dynamics [77–79]. The depopulation of mountain and rural areas in favor of urban and coastal areas causes the transformation of the territory. For example, in rural and mountainous areas, the abandonment of agricultural areas and pastures causes various phenomena such as soil erosion, hydrogeological instability and loss of biodiversity. Even in urban areas, soil consumption produces a loss of ESs with risks to the safety and health of citizens. Urban flooding has become increasingly frequent due to increased urbanization and climate change [80]. Urban green spaces can play an important role in reducing flooding [81]. Investing in urban green spaces and green infrastructure could therefore help strengthen the resilience of territories against climate change.

In the specifics of the distribution of the coefficient values collected in our database, we found the following features: (i) the range of values is generally greater in the regulating ES than in the provisioning ones; (ii) the range of values is generally greater for economic values than for biophysical ones; and (iii) the range of values generally increases as the studies considered increase (and therefore the number of coefficients extracted), e.g., for forest classes. The first point can be explained largely by the fact that the analysis of provisioning services is very often based on point accounts, which can be found in official statistical systems, whereas regulating services are not often included in this type of statistics but are evaluated employing heterogeneous methodologies, which often have a higher degree of approximation. Concerning the second point, the higher variability of economic values compared to biophysical ones stems from the fact that the latter suffers from a double variability since they are both usually derived from biophysical values (with their intrinsic variability), and from the use of non-standardized economic values (see the social cost of carbon, as a case in point).

The economic supply values of the ESs found for the two years are in some cases within the ranges found in other works at the national level [82] while in other cases, they are outside these ranges. The difference can be attributed, at least in part, to the methodologies of employed analysis. A good example in this sense comes from the quantification reported in the IV report on Italian natural capital [82] where, through the use of ARIES technology, the economic value of a service is estimated based on the degree of protection of potentially floodable assets (calculation of avoided damage). On the contrary, in our work, the economic coefficients extracted from the literature refer mainly to the 'replacement cost', i.e., the cost of building a lamination basin that can collect a given amount of rainwater. We estimated the annual cost of the infrastructure as a function of the construction cost [83] and the average infrastructure duration of 25 years.

At the same time, the same report attributes the value of the groundwater recharge service in 2018 at approximately EUR 14,073 million (values as of 2018), similar to the value found in our study (16,115 million), especially if we consider that our values are indeed attributed to land cover in the year 2018, but are discounted in economic terms to 2022.

Concerning the total economic change in services from 1990 to 2018 found in our paper, although at first glance it may not seem particularly relevant (a decrease of about EUR 927 million out of a total supply in 1990 of 98.5 billion), this becomes more significant if one considers that the change found concerns only the difference in the supply of ESs generated by land cover in 2018, compared to land cover in 1990. Our results therefore do not include the total annual changes in ES supply that occurred between 1990 and 2018, but only the differential between the supply capacity in 1990 and that in 2018. If we hypothetically assume a linear trend of decreasing ES supply in the 28 years between 1990 and 2018, we would have to count (i.e., sum) the losses that occurred year by year over the entire period. The final accounting would be higher in this case.

Our study thus highlights how the capacity of the Italian territory to generate ecosystem services has decreased in 2018 compared to 1990. As reflected in the international literature [21,22,84], the decrease in ecosystem services is a global issue. IPBES [8], for example, calculates that globally from 1970 to 2019, 14 of the 18 ESs analyzed are decreasing. The increases are only in the ES of potential food and bioenergy production resulting from the expansion of agricultural land globally. However, agricultural area expansion (along with urbanization and deforestation) is among the land-use changes that most impact other ESs. In our case, economic ES supply variation was analyzed through the transition categories approach to point out the weight that each land-use change had on the ES variation. In this sense, this study finds a remarkable correspondence between food production and agricultural intensification, which is the most important factor of the total fluctuation. This correspondence can be found especially in some regions, such as Veneto and Sicily.

In our opinion, an added value of this work is that the approach adopted allows for the distinction of spatial processes that lead to "synergies" and "trade-offs" in the provision of ESs. Synergies consist of a simultaneous increase or decrease in service provision as a result of the same driver of change (LULC changes in our case), while trade-offs involve opposite changes in service provision [85]. A good example in terms of trade-offs comes again from agricultural intensification which brings increased food and forage production but at the expense of many other services (notably air purification, erosion protection and global climate regulation). These results are in line with the international literature [86,87] and derive from the simplification of the landscape that agricultural intensification brings with it. In particular, in the Italian case we analyzed, the processes of agricultural intensification mainly involved [87] the transition from heterogeneous agricultural and semi-forested areas to arable land and permanent crops (vineyards in particular). A possible solution to mitigate the adverse effects of agricultural intensification on the provision of many regulating ESs is offered by "agroecology", which seeks a better balance between purely productive outputs and the conservation of natural capital [88–92].Another exemplary case concerns reforestation processes, which account for almost 14% in area of the total permanence and transitions, and generate a positive synergy for all ESs, but the trade-offs are those typical of agricultural areas such as food and forage production. In this case, synergies involve those ESs that are typically generated by forests and also defined in the literature as "bundles of ESs" [93], namely "a set of associated ESs that are linked to a given ecosystem and that usually appear together repeatedly in time and/or space" [94]. Other examples of synergy, in this case with negative effects, are urbanization and evolution into complex systems transitions.

The former, as might be expected, leads to a reduction in all ESs, while the latter in almost all. In fact, urbanization (except in the case of the establishment of urban green areas), leads to a major loss of natural capital and generated ESs. While the evolution to a complex system involves a significant net reduction in ESs, because, as we have noted, this transition occurs primarily at the expense of agricultural and forestry land uses which are known to provide high provisioning (the former) and regulating (the latter) services.

In general, the practice of analyzing spatial dynamics in terms of synergies, trade-offs and ES bundles can be a useful tool for managing a territory with greater awareness and in our opinion should be integrated into spatial planning processes. In particular, the results of this study on trade-offs and synergies arising from LULC changes could be a good information basis for specific cost–benefit analyses and/or for informing local spatial planning on the many complex effects of certain decisions.

Limitations of the Study and Future Steps

It is important to highlight that in this paper, the economic estimation of ESs was carried out using benefit transfer. Benefit transfer is a method that allows for a relatively quick assessment of the value of ecosystem services, but at the same time can be a source of errors in the assessment. One of the main errors in the use of benefit transfer is what the literature refers to as 'generalization', i.e., the lack of correspondence between the site from which values are taken ('study site') and the one to which they are transferred ('policy site') [44,95,96]. To limit this approximation, in this work, the CLC class at Level III was used as the initial minimum unit of analysis. To the best of our knowledge, this level of detail is used in very few studies, as most refer to biomes with lower resolution. Thus, using this level of detail, values can be transferred between land use and land cover units with a fair degree of correspondence. Furthermore, it should be emphasized that our case study is the entire Italian national territory, which, with its multitude of climates, biomes and territorial configurations, already presents intrinsic variability in the provision of ecosystem services. In this sense, therefore, the variability of the values that we have found in our study, may even be less than the variability that would be obtained by analyzing Italian biodiversity with other, more analytical methods. Similarly, applying a single method of analysis for the entire Italian territory would not necessarily lead to greater precision in estimation, since in any case, it is very likely that it would have to resort to approximations or generalizations to include the great variability of the structures, processes and conditions of Italy's natural capital that underlie the generation of ecosystem services. We believe, therefore, that the benefit transfer method used herein fits well with the purpose of this work, which does not reside in a punctual and local analysis of the provision of ESs, but in the most representative, albeit approximate, value of the average capacity to provide ecosystem services. In our study we tried to acquire as many articles as possible to extrapolate ES biophysical and economic unit values for land cover classes. Despite our efforts, not all ESs potentially generated in the Italian territory have been considered. This is probably also reflected in the results, e.g., we found that the main drivers of the ES economic value variation at the national level can be associated with the decrease in food production that, despite the boost of agricultural intensification, is reduced by other transitions (e.g., urbanization, forest expansion). In this regard, it is necessary to point out that, by not counting all possible ESs provided by forests, our study inevitably underestimates the economic value of reforestation. Among the services provided by forests and not valued in this study, we find, for example, recreational and heat wave mitigation services. Counting, among others, these two services could certainly increase the economic value obtained from reforestation processes. In any case, it should also be noted that many of the ESs provided by forests are not accounted for in an official market and therefore their value is more difficult to derive. In this sense, new accountings such as the SEEA framework [97] are therefore crucial, precisely in order not to further neglect the benefits provided by forests.

Among the ESs not analyzed in this paper are cultural services in particular. Due to methodological challenges, cultural ESs are rarely fully considered in ES assessments [98]. In fact, research on cultural ESs requires alternative assessment approaches that draw on a wide range of social science tools and methods [99]. Therefore, to integrate cultural ESs into our evaluation, specific investigations of biophysical and economic evaluations should be conducted for CLC classes at the national scale.

In the future, it will be necessary to try to include, through specific coefficients, the contribution of cultural ESs to the overall provision of services, but this operation requires a deep reflection from a methodological point of view and careful use of the results. In fact, cultural ESs, by their very characteristics, are related to the cultural capital of populations and this makes the interaction between man and the environment that is the basis of cultural ESs [84] extremely variable—for the same land use, or even for the same biomes or ecosystems. One of the future challenges of our research is to implement specific survey methods such as participatory approaches [56,57] or the use of the Social Values for Ecosystem Services (SolVES) software to have biophysical and economic coefficients for cultural ESs. Furthermore, to expand the database that we created, we aim to improve the literature research using other search engines such as Web of Science (WOS) and to review the keywords. We will also expand the bibliographic research considering a broader time than the one considered. This would allow us to find more articles from which to extract biophysical and economic coefficients and obtain greater coverage in terms of the considered ESs.

Finally, the methodological combination applied in this study also allows an analysis of the trade-offs and synergies of ESs resulting from LULC changes, which are potentially very useful in spatial planning processes. Future research directions in this regard could explore the role of synergy and trade-off analysis in order to meet the specific ES demands found in a given area. In the same way, it would be very useful to further investigate the relationship between provisioning and regulating services, providing suggestions on how to optimize service provision with a view to balanced spatial planning that generates 'win-win' results, according to the identified needs.

5. Conclusions

Compared to other studies conducted in Italy, the original contribution of our research is to present an approach for assessing the impacts of LULC changes on the provision of ESs using the combination of transition matrices with biophysical and economic coefficients from the literature. In comparison to ISPRA (2022), which analyzes the impacts of land consumption, urbanization and infrastructure on the landscape and ESs, we analyzed the assessment of ESs as a function of the transition and permanence processes over a broad period (1990–2018). Furthermore, compared to the IV report on Italian natural capital [84], we extrapolated a large set of biophysical and economic data from the literature. This analysis could be used to predict future scenarios to support mitigation and adaptation strategies and policies.

The proposed approach is versatile and can be applied in other spatial contexts since the matrices and coefficients are associated with Corine land use classes. In fact, by knowing the extent of land cover classes and the unit values (biophysical and economic) per hectare, it is possible to estimate both the supply of ESs and its resulting variation due to changes in LULC. In this sense, the results of this study can also be used as a predictive tool in regional or urban planning. The negative consequences of soil sealing, for example, cannot be completely mitigated by afforestation interventions (in case, e.g., of environmental offset) since the significant ES loss is not compensated by the possible increases.

The presented approach has been applied to implement the study by Marino et al., 2022 [48] and provide a synthesis of the variations in the economic value of ESs observed in Italy in the period 1990–2018 caused by the transition and permanence processes. The study, of which this work is a part, is oriented to promoting methodologies for the estimation of ESs, contributing to enriching the scientific literature on this topic. In fact, there are many studies in the literature and the authors (Appendix A) have used different software, methodologies and approaches to quantify and assess ESs at the biome level [22], ecosystem level [100], and land cover classes (see studies listed in Appendix A). The study by land cover classes has the advantage of measuring, with greater precision and detail, the impact of land transformation processes on ES supply. Furthermore, the constant updates of Corine data at a European level allow applications at different spatial and temporal scales.

The results of this study are open to comparison, to improve the proposed approach to ES assessment, to update the coefficients from new studies and to deepen the spatial distribution through the use of some geographic detectors (e.g., Markow chain and Gini coefficient). However, our challenge will be to augment the database with other coefficients (biophysical and economic) by improving the literature review. The proposed approach may be functional for monitoring ESs at spatial and temporal scales as a function of land transformation process support for the implementation of SEEA Ecosystem Accounting (SEEA EA) to account for ESs [97]. Environmental accounting tools can support public decision-makers in choosing policies and strategies for global and local governance.

Author Contributions: Conceptualization, D.M. and M.P.; methodology, D.M., M.P., A.M. and A.B.; software, A.B. and S.P.; formal analysis, A.B. and S.P.; investigation, A.B., A.M. and M.P.; data curation, A.B. and A.M.; writing—original draft preparation, A.B., M.P. and A.M.; writing—review and editing, M.P., A.M., A.B. and S.P.; visualization, A.B. and S.P.; supervision, D.M., A.M. and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Bibliographic references of biophysical and economic coefficients. Note: The articles are listed in the references.

ES	Sources	Biophysical Coefficient	Economic Coefficient	Study Area
Food production	Council for Agricultural Research and Economics, 2022 [52]	×	×	Italy
Forage production	Schirpke et al., 2015 [101]	×	×	Natura 2000 Sites (Italy)
	Marino et al., 2021 [2]	×	×	National Parks (Italy)
	Tardieu et al., 2015 [102]	×	×	Natural and semi-natural areas (France)
Timber supply	Grilli et al., 2015 [103]		×	Italian Alps
	Häyhä et al., 2015 [36]	×	×	Alpine forests (Italy)
	Vysna et al., 2019 [100]	×	×	Europe
	Pedroso et al., 2018 [104]		×	Natural Park of Serra de São Mamede, Portugal
	Bernetti et al., 2013 [105]		×	Forest area of Tuscany (Italy)
	Pettenella et al., 2021 [106]	×		Forests in the Veneto region (Italy)
	Hein et al., 2011 [107]	×	×	Hoge Veluwe protected forest (Netherlands)
	White, 2015 [108]	×	×	Protected areas in England and Scotland
	Marchetti et al., 2018 [109]	×	×	Italians forest
Mushrooms supply	Schirpke et al., 2015 [101]	×	×	Natura 2000 Sites (Italy)
	Bernetti et al., 2013 [105]	×	×	Toscana Region (Italy)
Global climate regulation	De Jong et al., 2016 [110]	×		Limburg Province (Netherlands)
	Remme et al., 2016 [111]		×	Limburg Province (Netherlands)
	Marino et al., 2021 [2]	×	×	National Parks (Italy)
	Schirpke et al., 2015 [101]	×	×	Natura 2000 Sites (Italy)
	Morri et al., 2014 [83]	×	×	Apennines and coastal areas (Italy)
	Häyhä et al., 2015 [36]	×	×	Alpine forests (Italy)
	Cervelli et al., 2022 [112]		×	Vesuvius National Park (Italy)
	Paletto et al., 2015 [113]		×	Austrian Alps
	Bernetti et al., 2013 [105]		×	Forest area of Tuscany (Italy)
	White, 2015 [108]	×	×	Protected areas in England and Scotland

Table A1. *Cont.*

ES	Sources	Biophysical Coefficient	Economic Coefficient	Study Area
Global climate regulation	Willis et al., 2003 [114]		×	Forests (Great Britain)
	Xue et al., 2001 [115]	×	×	Changbaishan Mountain Biosphere Reserve (Northeast China)
	Marino et al., eds (2023) [60]	×	×	Monte Amiata e Mugello, Toscana (Italy)
	Marino et al., eds (2023) [116]	×	×	Città metropolitana Roma Capitale (Italy)
Air purification	De Jong et al., 2016 [110]	×		Limburg Province (Netherlands)
	Remme et al., 2016 [111]		×	Limburg Province (Netherlands)
	Duarte et al., 2021 [117]		×	Salt marsh plant species of six Portuguese transitional systems
	Marino et al., 2021 [2]	×	×	National Parks (Italy)
	Bottalico et al., 2016 [54]	×		Florence (Italy)
	Manes et al., 2014 [53]	×		Rome (Italy)
	Hein, 2011 [107]	×	×	Hoge Veluwe protected forest (Netherlands)
	White, 2015 [108]	×	×	Protected areas in England and Scotland
	Marino et al., eds (2023) [60]	×	×	Monte Amiata e Mugello, Toscana (Italy)
Water regulation	De Jong, 2016 [110]	×		Limburg Province (Netherlands)
	Remme, 2016 [111]		×	Limburg Province (Netherlands)
	Duarte et al., 2021 [117]		×	Salt marsh plant species of six Portuguese transitional systems
	Schirpke et al., 2015 [101]	×		Natura 2000 Sites (Italy)
	Bernetti et al., 2013 [105]		×	Toscana Region (Italy)
	Hein et al., 2011 [107]	×	×	Hoge Veluwe protected forest (Netherlands)
	Esen et al., 2023 [118]	×	×	Forest in Southern Aegean region of Turkey
	Xue et al., 2001 [115]	×	×	Changbaishan Mountain Biosphere Reserve (Northeast China)
Water purification	Duarte et al., 2021 [117]		×	Salt marsh plant species of six Portuguese transitional systems
	Marino et al., eds (2023) [60]	×	×	Monte Amiata e Mugello, Toscana (Italy)

Table A1. *Cont.*

ES	Sources	Biophysical Coefficient	Economic Coefficient	Study Area
Water purification	Marino (eds), 2023 [116]	×	×	Città metropolitana Roma Capitale (Italy)
	Piaggio et al., 2021 [119]		×	Forest areas (Costa Rica)
	Mueller et al., 2014 [120]		×	Forest in northern Arizona (USA)
	De la Cruz et al., 2009 [121]		×	Pico da Vara Special Protected Area (Portugal)
	Matero et al., 2007 [122]		×	Finnish forests (Finland)
Erosion protection	Esen et al., 2023 [118]	×	×	Forest in Southern Aegean region of Turkey
	Duarte et al., 2021 [117]		×	Salt marsh plant species of six Portuguese transitional systems
	Schirpke et al., 2015 [101]	×	×	Natura 2000 Sites (Italy)
	Marino et al., eds (2023) [60]	×	×	Monte Amiata e Mugello, Toscana (Italy)
	Mastrorilli et al., 2018 [123]	×	×	Calabria Region, Italy
	Morri et al., 2014 [83]	×	×	Apennines and coastal areas (Italy)
	Häyhä et al., 2015 [36]		×	Alpine forests (Italy)
	Pedroso et al., 2018 [104]		×	Natural Park of Serra de São Mamede, Portugal
	Xue et al., 2001 [115]		×	Changbaishan Mountain Biosphere Reserve (Northeast China)
Flood risk mitigation	Esen et al., 2023 [118]		×	Forest in Southern Aegean region of Turkey
	Duarte et al., 2021 [117]		×	Salt marsh plant species of six Portuguese transitional systems
	Marino et al., eds (2023) [60]	×	×	Monte Amiata e Mugello, Toscana (Italy)
	Morri et al., 2014 [83]	×	×	Apennines and coastal areas (Italy)
	Mastrorilli et al., 2018 [123]	×	×	Calabria Region, Italy
	Marino et al., 2023 [49]	×	×	Città metropolitana Roma Capitale (Italy)
	Broadmeadow et al., 2018 [124]		×	Forest in Great Britain (GB)

References

1. Steffen, W.; Crutzen, P.J.; McNeill, J.R. The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature? *Ambio* **2007**, *36*, 614–621. Available online: http://www.jstor.org/stable/25547826 (accessed on 30 March 2023). [CrossRef] [PubMed]
2. Marino, D.; Palmieri, M.; Marucci, A.; Tufano, M. Comparison between Demand and Supply of Some Ecosystem Services in National Parks: A Spatial Analysis Conducted Using Italian Case Studies. *Conservation* **2021**, *1*, 36–57. [CrossRef]

3. Ellis, E.C.; Goldewijk, K.K.; Siebert, S.; Lightman, D.; Ramankutty, N. Anthropogenic Transformation of the Biomes, 1700 to 2000. *Glob. Ecol. Biogeogr.* **2010**, *19*, 589–606. [CrossRef]
4. Fang, Z.; Ding, T.; Chen, J.; Xue, S.; Zhou, Q.; Wang, Y.; Wang, Y.; Huang, Z.; Yang, S. Impacts of Land Use/Land Cover Changes on Ecosystem Services in Ecologically Fragile Regions. *Sci. Total Environ.* **2022**, *831*, 154967. [CrossRef] [PubMed]
5. Hasan, S.S.; Zhen, L.; Miah, M.G.; Ahamed, T.; Samie, A. Impact of Land Use Change on Ecosystem Services: A Review. *Environ. Dev.* **2020**, *34*, 100527. [CrossRef]
6. Zhang, Z.; Liu, Y.; Wang, Y.; Liu, Y.; Zhang, Y.; Zhang, Y. What Factors Affect the Synergy and Tradeoff between Ecosystem Services, and How, from a Geospatial Perspective? *J. Clean. Prod.* **2020**, *257*, 120454. [CrossRef]
7. Davison, C.W.; Rahbek, C.; Morueta-Holme, N. Land-Use Change and Biodiversity: Challenges for Assembling Evidence on the Greatest Threat to Nature. *Glob. Chang. Biol.* **2021**, *27*, 5414–5429. [CrossRef]
8. IPBES. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services*; IPBES: Bonn, Germany, 2019; Volume 45, ISBN 9783947851133.
9. Beckmann, M.; Gerstner, K.; Akin-Fajiye, M.; Ceaușu, S.; Kambach, S.; Kinlock, N.L.; Phillips, H.R.P.; Verhagen, W.; Gurevitch, J.; Klotz, S.; et al. Conventional Land-Use Intensification Reduces Species Richness and Increases Production: A Global Meta-Analysis. *Glob. Chang. Biol.* **2019**, *25*, 1941–1956. [CrossRef]
10. Gerstner, K.; Dormann, C.F.; Stein, A.; Manceur, A.M.; Seppelt, R. Effects of Land Use on Plant Diversity—A Global Meta-Analysis. *J. Appl. Ecol.* **2014**, *51*, 1690–1700. [CrossRef]
11. Newbold, T.; Hudson, L.N.; Hill, S.L.L.; Contu, S.; Gray, C.L.; Scharlemann, J.P.W.; Börger, L.; Phillips, H.R.P.; Sheil, D.; Lysenko, I.; et al. Global Patterns of Terrestrial Assemblage Turnover within and among Land Uses. *Ecography* **2016**, *39*, 1151–1163. [CrossRef]
12. Aronson, M.F.J.; La Sorte, F.A.; Nilon, C.H.; Katti, M.; Goddard, M.A.; Lepczyk, C.A.; Warren, P.S.; Williams, N.S.G.; Cilliers, S.; Clarkson, B.; et al. A Global Analysis of the Impacts of Urbanization on Bird and Plant Diversity Reveals Key Anthropogenic Drivers. *Proc. R. Soc. B Biol. Sci.* **2014**, *281*, 20133330. [CrossRef] [PubMed]
13. Murphy, G.E.P.; Romanuk, T.N. A Meta-Analysis of Declines in Local Species Richness from Human Disturbances. *Ecol. Evol.* **2014**, *4*, 91–103. [CrossRef] [PubMed]
14. Admasu, S.; Yeshitela, K.; Argaw, M. Impact of Land Use Land Cover Changes on Ecosystem Service Values in the Dire and Legedadi Watersheds, Central Highlands of Ethiopia: Implication for Landscape Management Decision Making. *Heliyon* **2023**, *9*, e15352. [CrossRef] [PubMed]
15. Benítez, F.L.; Mena, C.F.; Zurita-Arthos, L. Urban Land Cover Change in Ecologically Fragile Environments: The Case of the Galapagos Islands. *Land* **2018**, *7*, 21. [CrossRef]
16. Burkhard, B.; Kroll, F.; Müller, F.; Windhorst, W. Landscapes' Capacities to Provide Ecosystem Services—A Concept for Land-Cover Based Assessments. *Landsc. Online* **2009**, *15*, 1–22. [CrossRef]
17. Sharma, R.; Rimal, B.; Baral, H.; Nehren, U.; Paudyal, K.; Sharma, S.; Rijal, S.; Ranpal, S.; Acharya, R.P.; Alenazy, A.A.; et al. Impact of Land Cover Change on Ecosystem Services in a Tropical Forested Landscape. *Resources* **2019**, *8*, 18. [CrossRef]
18. Hailu, A.; Mammo, S.; Kidane, M. Dynamics of Land Use, Land Cover Change Trend and Its Drivers in Jimma Geneti District, Western Ethiopia. *Land Use Policy* **2020**, *99*, 105011. [CrossRef]
19. Maes, J.; Liquete, C.; Teller, A.; Erhard, M.; Paracchini, M.L.; Barredo, J.I.; Grizzetti, B.; Cardoso, A.; Somma, F.; Petersen, J.E.; et al. An Indicator Framework for Assessing Ecosystem Services in Support of the EU Biodiversity Strategy to 2020. *Ecosyst. Serv.* **2016**, *17*, 14–23. [CrossRef]
20. Potschin, M.B.; Haines-Young, R.H. Ecosystem Services: Exploring a Geographical Perspective. *Prog. Phys. Geogr.* **2011**, *35*, 575–594. [CrossRef]
21. Costanza, R.; D'Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J.; et al. The Value of the World's Ecosystem Services and Natural Capital. *Ecol. Econ.* **1998**, *25*, 3–15. [CrossRef]
22. Costanza, R.; de Groot, R.; Sutton, P.; van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the Global Value of Ecosystem Services. *Glob. Environ. Chang.* **2014**, *26*, 152–158. [CrossRef]
23. De Vreese, R.; Leys, M.; Fontaine, C.M.; Dendoncker, N. Social Mapping of Perceived Ecosystem Services Supply-The Role of Social Landscape Metrics and Social Hotspots for Integrated Ecosystem Services Assessment, Landscape Planning and Management. *Ecol. Indic.* **2016**, *66*, 517–533. [CrossRef]
24. Plieninger, T.; Dijks, S.; Oteros-Rozas, E.; Bieling, C. Assessing, Mapping, and Quantifying Cultural Ecosystem Services at Community Level. *Land Use Policy* **2013**, *33*, 118–129. [CrossRef]
25. van Riper, C.J.; Kyle, G.T.; Sutton, S.G.; Barnes, M.; Sherrouse, B.C. Mapping Outdoor Recreationists' Perceived Social Values for Ecosystem Services at Hinchinbrook Island National Park, Australia. *Appl. Geogr.* **2012**, *35*, 164–173. [CrossRef]
26. Burkhard, B.; Kandziora, M.; Hou, Y.; Müller, F. Ecosystem Service Potentials, Flows and Demands-Concepts for Spatial Localisation, Indication and Quantification. *Landsc. Online* **2014**, *34*, 1–32. [CrossRef]
27. Schirpke, U.; Tasser, E. Trends in Ecosystem Services across Europe Due to Land-Use/Cover Changes. *Sustainability* **2021**, *13*, 7095. [CrossRef]
28. Ongsomwang, S.; Pattanakiat, S.; Srisuwan, A. Impact of Land Use and Land Cover Change on Ecosystem Service Values: A Case Study of Khon Kaen City, Thailand. *Environ. Nat. Resour. J.* **2019**, *17*, 43–58. [CrossRef]

29. Wang, H.; Lü, Z.; Gu, L.; Wen, C.; Palomo-Campesino, S.; García-Llorente, M.; Hevia, V.; Boeraeve, F.; Dendoncker, N.; González, J.A.; et al. Linking Flood Risk Mitigation and Food Security: An Analysis of Land-Use Change in the Metropolitan Area of Rome. *Ecosyst. Serv.* **2021**, *11*, 1–23.
30. Assefa, G.; Kijora, C.; Kehaliew, A.; Sonder, K.; Peters, K.J. Effect of Pre-Feeding Forage Treatments, Harvesting Stage, and Animal Type on Preference of Tagasaste (*Chamaecytisus palmensis*). *Agrofor. Syst.* **2012**, *84*, 25–34. [CrossRef]
31. Gashaw, T.; Tulu, T.; Argaw, M.; Worqlul, A.W. Evaluation and Prediction of Land Use/Land Cover Changes in the Andassa Watershed, Blue Nile Basin, Ethiopia. *Environ. Syst. Res.* **2017**, *6*, 17. [CrossRef]
32. Berihun, M.L.; Tsunekawa, A.; Haregeweyn, N.; Meshesha, D.T.; Adgo, E.; Tsubo, M.; Masunaga, T.; Fenta, A.A.; Sultan, D.; Yibeltal, M. Exploring Land Use/Land Cover Changes, Drivers and Their Implications in Contrasting Agro-Ecological Environments of Ethiopia. *Land Use Policy* **2019**, *87*, 104052. [CrossRef]
33. Ciocănea, C.M.; Sorescu, C.; Ianoşi, M.; Bagrinovschi, V. Assessing Public Perception on Protected Areas in Iron Gates Natural Park. *Procedia Environ. Sci.* **2016**, *32*, 70–79. [CrossRef]
34. Lin, J.; Huang, J.; Prell, C.; Bryan, B.A. Changes in Supply and Demand Mediate the Effects of Land-Use Change on Freshwater Ecosystem Services Flows. *Sci. Total Environ.* **2021**, *763*, 143012. [CrossRef] [PubMed]
35. Chen, W.; Zhao, H.; Li, J.; Zhu, L.; Wang, Z.; Zeng, J. Land Use Transitions and the Associated Impacts on Ecosystem Services in the Middle Reaches of the Yangtze River Economic Belt in China Based on the Geo-Informatic Tupu Method. *Sci. Total Environ.* **2020**, *701*, 134690. [CrossRef] [PubMed]
36. Häyhä, T.; Franzese, P.P.; Paletto, A.; Fath, B.D. Assessing, Valuing, and Mapping Ecosystem Services in Alpine Forests. *Ecosyst. Serv.* **2015**, *14*, 12–23. [CrossRef]
37. Urbina-Cardona, N.; Cardona, V.O.; Cuellar, S. Uncovering Thematic Biases in Ecosystem Services Mapping: Knowledge Shortfalls and Challenges for Use in Conservation. *Biol. Conserv.* **2023**, *283*, 110086. [CrossRef]
38. Leal Filho, W.; Azeiteiro, U.M.; Balogun, A.L.; Setti, A.F.F.; Mucova, S.A.R.; Ayal, D.; Totin, E.; Lydia, A.M.; Kalaba, F.K.; Oguge, N.O. The Influence of Ecosystems Services Depletion to Climate Change Adaptation Efforts in Africa. *Sci. Total Environ.* **2021**, *779*, 146414. [CrossRef]
39. Brouwer, R. Environmental Value Transfer: State of the Art and Future Prospects. *Ecol. Econ.* **2000**, *32*, 137–152. [CrossRef]
40. Desvousges, W.H.; Naughton, M.C.; Parsons, G.R. Benefit Transfer: Conceptual Problems in Estimating Water Quality Benefits Using Existing Studies. *Water Resour. Res.* **1992**, *28*, 675–683. [CrossRef]
41. Bateman, I.J.; Brouwer, R.; Ferrini, S.; Schaafsma, M.; Barton, D.N.; Dubgaard, A.; Hasler, B.; Hime, S.; Liekens, I.; Navrud, S.; et al. Making Benefit Transfers Work: Deriving and Testing Principles for Value Transfers for Similar and Dissimilar Sites Using a Case Study of the Non-Market Benefits of Water Quality Improvements Across Europe. *Environ. Resour. Econ.* **2011**, *50*, 365–387. [CrossRef]
42. Rosenberger, R.S.; Stanley, T.D. Measurement, Generalization, and Publication: Sources of Error in Benefit Transfers and Their Management. *Ecol. Econ.* **2006**, *60*, 372–378. [CrossRef]
43. Boutwell, J.L.; Westra, J.V. Benefit Transfer: A Review of Methodologies and Challenges. *Resources* **2013**, *2*, 517–527. [CrossRef]
44. Richardson, L.; Loomis, J.; Kroeger, T.; Casey, F. The Role of Benefit Transfer in Ecosystem Service Valuation. *Ecol. Econ.* **2015**, *115*, 51–58. [CrossRef]
45. Ecosystem Services Valuation Database. Available online: https://www.esvd.info/ (accessed on 8 August 2023).
46. The Environmental Valuation Reference. Inventory. Available online: https://evri.ca/en (accessed on 8 August 2023).
47. INCA Platform. Available online: https://ecosystem-accounts.jrc.ec.europa.eu/ (accessed on 8 August 2023).
48. Marino, D.; Palmieri, M.; Marucci, A.; Pili, S. Long-Term Land Cover Changes and Ecosystem Services Variation: Have the Anthropogenic Transformations Degraded Human Well-Being in Italy? *Ital. Rev. Agric. Econ.* **2022**, *77*, 7–23. [CrossRef]
49. Marino, D.; Palmieri, M.; Marucci, A.; Soraci, M.; Barone, A.; Pili, S. Linking Flood Risk Mitigation and Food Security: An Analysis of Land-Use Change in the Metropolitan Area of Rome. *Land* **2023**, *12*, 366. [CrossRef]
50. SCOPUS. Available online: https://www.scopus.com/ (accessed on 30 March 2023).
51. Italian Institute of Statistics (ISTAT). Available online: https://www.istat.it/it/agricoltura?dati (accessed on 8 August 2023).
52. CREA. *Annuario Dell'Agricoltura Itialiana*; CREA: Roma, Italy, 2021; ISBN 9788833851532.
53. Manes, F.; Silli, V.; Salvatori, E.; Incerti, G.; Galante, G.; Fusaro, L.; Perrino, C. Urban Ecosystem Services: Tree Diversity and Stability of PM10 Removal in the Metropolitan Area of Rome. *Ann. Bot.* **2014**, *4*, 19–26. [CrossRef]
54. Bottalico, F.; Chirici, G.; Giannetti, F.; De Marco, A.; Nocentini, S.; Paoletti, E.; Salbitano, F.; Sanesi, G.; Serenelli, C.; Travaglini, D. Air Pollution Removal by Green Infrastructures and Urban Forests in the City of Florence. *Agric. Agric. Sci. Procedia* **2016**, *8*, 243–251. [CrossRef]
55. Crouzat, E.; De Frutos, A.; Grescho, V.; Carver, S.; Büermann, A.; Carvalho-Santos, C.; Kraemer, R.; Mayor, S.; Pöpperl, F.; Rossi, C.; et al. Potential Supply and Actual Use of Cultural Ecosystem Services in Mountain Protected Areas and Their Surroundings. *Ecosyst. Serv.* **2022**, *53*, 101395. [CrossRef]
56. Schirpke, U.; Timmermann, F.; Tappeiner, U.; Tasser, E. Cultural Ecosystem Services of Mountain Regions: Modelling the Aesthetic Value. *Ecol. Indic.* **2016**, *69*, 78–90. [CrossRef]
57. van Riper, C.J.; Kyle, G.T.; Sherrouse, B.C.; Bagstad, K.J.; Sutton, S.G. Toward an Integrated Understanding of Perceived Biodiversity Values and Environmental Conditions in a National Park. *Ecol. Indic.* **2017**, *72*, 278–287. [CrossRef]
58. ISTAT. Available online: https://rivaluta.istat.it/Rivaluta/ (accessed on 8 August 2023).

59. Manikandan, S. Measures of Central Tendency: Median and Mode. *J. Pharmacol. Pharmacother.* **2011**, *2*, 214–215. [CrossRef] [PubMed]
60. Marino, D.; Poli, D.; Rovai, M.; Butelli, E.; Marucci, A.; Trinchetti, T. *Montagna, Servizi Ecosistemici, e Strumenti Di Governance in Toscana*; I libri Della Giunta Regionale–Società: Toscana, Italy, 2022; Volume 5, ISBN 09788870401516.
61. Rasmussen, L.V.; Mertz, O.; Christensen, A.E.; Danielsen, F.; Dawson, N.; Xaydongvanh, P. A Combination of Methods Needed to Assess the Actual Use of Provisioning Ecosystem Services. *Ecosyst. Serv.* **2016**, *17*, 75–86. [CrossRef]
62. Ricke, K.; Drouet, L.; Caldeira, K.; Tavoni, M. Country-Level Social Cost of Carbon. *Nat. Clim. Chang.* **2018**, *8*, 895–900. [CrossRef]
63. Mangala, S.; Toppo, P.; Ghoshal, S. Study of Infiltration Capacity of Different Soils. *Int. J. Trend Res. Dev.* **2016**, *3*, 2394–9333.
64. Levavasseur, F.; Bailly, J.S.; Lagacherie, P.; Colin, F.; Rabotin, M. Simulating the Effects of Spatial Configurations of Agricultural Ditch Drainage Networks on Surface Runoff from Agricultural Catchments. *Hydrol. Process.* **2012**, *26*, 3393–3404. [CrossRef]
65. Irham, M.; Ilhamsyah, Y.; Sugianto; Deli, A.; Syahreza, S. Is Flash Flood Cycle? A Preliminary Climate Study on Teunom Fluvial System. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *273*, 012001. [CrossRef]
66. Nowak, D.J. Institutionalizing Urban Forestry as a 'Biotechnology' to Improve Environmental Quality. *Urban For. Urban Green.* **2006**, *5*, 93–100. [CrossRef]
67. Escobedo, F.J.; Nowak, D.J. Spatial Heterogeneity and Air Pollution Removal by an Urban Forest. *Landsc. Urban Plan.* **2009**, *90*, 102–110. [CrossRef]
68. Derkzen, M.L.; Nagendra, H.; Van Teeffelen, A.J.A.; Purushotham, A.; Verburg, P.H. Shifts in Ecosystem Services in Deprived Urban Areas: Understanding People's Responses and Consequences for Well-Being. *Ecol. Soc.* **2017**, *22*, 51. [CrossRef]
69. Niemelä, J. Ecology of Urban Green Spaces: The Way Forward in Answering Major Research Questions. *Landsc. Urban Plan.* **2014**, *125*, 298–303. [CrossRef]
70. Kindu, M.; Schneider, T.; Teketay, D.; Knoke, T. Changes of Ecosystem Service Values in Response to Land Use/Land Cover Dynamics in Munessa-Shashemene Landscape of the Ethiopian Highlands. *Sci. Total Environ.* **2016**, *547*, 137–147. [CrossRef] [PubMed]
71. Schirpke, U.; Leitinger, G.; Tasser, E.; Schermer, M.; Steinbacher, M.; Tappeiner, U. Multiple Ecosystem Services of a Changing Alpine Landscape: Past, Present and Future. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2013**, *9*, 123–135. [CrossRef] [PubMed]
72. Gomes, E.; Inácio, M.; Bogdzevič, K.; Kalinauskas, M.; Karnauskaitė, D.; Pereira, P. Future Land-Use Changes and Its Impacts on Terrestrial Ecosystem Services: A Review. *Sci. Total Environ.* **2021**, *781*, 146716. [CrossRef] [PubMed]
73. Belay, T.; Melese, T.; Senamaw, A. Impacts of Land Use and Land Cover Change on Ecosystem Service Values in the Afroalpine Area of Guna Mountain, Northwest Ethiopia. *Heliyon* **2022**, *8*, e12246. [CrossRef] [PubMed]
74. Tolessa, T.; Senbeta, F.; Kidane, M. The Impact of Land Use/Land Cover Change on Ecosystem Services in the Central Highlands of Ethiopia. *Ecosyst. Serv.* **2017**, *23*, 47–54. [CrossRef]
75. Subedi, Y.R.; Kristiansen, P.; Cacho, O. Drivers and Consequences of Agricultural Land Abandonment and Its Reutilisation Pathways: A Systematic Review. *Environ. Dev.* **2022**, *42*, 100681. [CrossRef]
76. Schirpke, U.; Tscholl, S.; Tasser, E. Spatio-Temporal Changes in Ecosystem Service Values: Effects of Land-Use Changes from Past to Future (1860–2100). *J. Environ. Manag.* **2020**, *272*, 111068. [CrossRef]
77. Li, J.; Chen, H.; Zhang, C.; Pan, T. Variations in Ecosystem Service Value in Response to Land Use/Land Cover Changes in Central Asia from 1995–2035. *PeerJ* **2019**, *7*, e7665. [CrossRef]
78. Xie, Y.; Mei, Y.; Guangjin, T.; Xuerong, X. Socio-Economic Driving Forces of Arable Land Conversion: A Case Study of Wuxian City, China. *Glob. Environ. Chang.* **2005**, *15*, 238–252. [CrossRef]
79. Shi, Y.; Wang, R.; Fan, L.; Li, J.; Yang, D. Analysis on Land-Use Change and Its Demographic Factors in the Original-Stream Watershed of Tarim River Based on GIS and Statistic. *Procedia Environ. Sci.* **2010**, *2*, 175–184. [CrossRef]
80. Kadaverugu, A.; Nageshwar Rao, C.; Viswanadh, G.K. Quantification of Flood Mitigation Services by Urban Green Spaces Using InVEST Model: A Case Study of Hyderabad City, India. *Model. Earth Syst. Environ.* **2021**, *7*, 589–602. [CrossRef]
81. Yang, B.; Lee, D. Urban Green Space Arrangement for an Optimal Landscape Planning Strategy for Runoff Reduction. *Land* **2021**, *10*, 897. [CrossRef]
82. Comitato per il Capitale Naturale. *Quarto Rapporto Sullo Stato del Capitale Naturale in Italia*; Comitato per Il Capitale Naturale: Roma, Italy, 2021. Available online: https://www.mase.gov.it/pagina/quarto-rapporto-sullo-stato-del-capitale-naturale-italia-2021 (accessed on 24 August 2023).
83. Morri, E.; Pruscini, F.; Scolozzi, R.; Santolini, R. A Forest Ecosystem Services Evaluation at the River Basin Scale: Supply and Demand between Coastal Areas and Upstream Lands (Italy). *Ecol. Indic.* **2014**, *37*, 210–219. [CrossRef]
84. Reid, W. *Ecosystems and Human Well-Being: A Report on the Conceptual Framework Working Group of the Millenium Ecosystem Assessment*; Island Press: Washington, DC, USA, 2005; Volume 5, ISBN 1559634022.
85. Rodríguez, J.P.; Beard, T.D.; Bennett, E.M.; Cumming, G.S.; Cork, S.J.; Agard, J.; Dobson, A.P.; Peterson, G.D. Trade-Offs across Space, Time, and Ecosystem Services. *Ecol. Soc.* **2006**, *11*, 28. [CrossRef]
86. Power, A.G. Ecosystem Services and Agriculture: Tradeoffs and Synergies. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 2959–2971. [CrossRef] [PubMed]
87. Watson, S.C.L.; Newton, A.C.; Ridding, L.E.; Evans, P.M.; Brand, S.; McCracken, M.; Gosal, A.S.; Bullock, J.M. Does Agricultural Intensification Cause Tipping Points in Ecosystem Services? *Landsc. Ecol.* **2021**, *36*, 3473–3491. [CrossRef]

88. Palomo-Campesino, S.; García-Llorente, M.; Hevia, V.; Boeraeve, F.; Dendoncker, N.; González, J.A. Do Agroecological Practices Enhance the Supply of Ecosystem Services? A Comparison between Agroecological and Conventional Horticultural Farms. *Ecosyst. Serv.* **2022**, *57*, 101474. [CrossRef]
89. Nentwig, W.; Gloor, D.; Kropf, C. Spider Taxonomists Catch Data on Web. *Nature* **2015**, *528*, 479. [CrossRef]
90. Boone, L.; Roldán-Ruiz, I.; Van linden, V.; Muylle, H.; Dewulf, J. Environmental Sustainability of Conventional and Organic Farming: Accounting for Ecosystem Services in Life Cycle Assessment. *Sci. Total Environ.* **2019**, *695*, 133841. [CrossRef]
91. Seitz, S.; Goebes, P.; Puerta, V.L.; Pereira, E.I.P.; Wittwer, R.; Six, J.; van der Heijden, M.G.A.; Scholten, T. Conservation Tillage and Organic Farming Reduce Soil Erosion. *Agron. Sustain. Dev.* **2019**, *39*, 4. [CrossRef]
92. Gattinger, A.; Muller, A.; Haeni, M.; Skinner, C.; Fliessbach, A.; Buchmann, N.; Mäder, P.; Stolze, M.; Smith, P.; Scialabba, N.E.H.; et al. Enhanced Top Soil Carbon Stocks under Organic Farming. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 18226–18231. [CrossRef] [PubMed]
93. Raudsepp-Hearne, C.; Peterson, G.D.; Bennett, E.M. Ecosystem Service Bundles for Analyzing Tradeoffs in Diverse Landscapes. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 5242–5247. [CrossRef] [PubMed]
94. Berry, P.; Turkelboom, F.; Verheyden, W.; Martín-López, B. Ecosystem Service Bundles. *OpenNESS* **2015**, *10*, 1–5.
95. Johnston, R.J.; Boyle, K.J.; Loureiro, M.L.; Navrud, S.; Rolfe, J. *Guidance to Enhance the Validity and Credibility of Environmental Benefit Transfers*; Springer: Dordrecht, The Netherlands, 2021; Volume 79, ISBN 0123456789.
96. Plummer, M.L. Assessing Benefit Transfer for the Valuation of Ecosystem Services. *Front. Ecol. Environ.* **2009**, *7*, 38–45. [CrossRef]
97. Hein, L.; Edens, B.; Obst, C.; Remme, R.; Schröter, M.; Sumarga, E. An Introduction to Ecosystem Accounting. *Routledge Handb. Ecosyst. Serv.* **2018**, 213–219. [CrossRef]
98. Plieninger, T.; Draux, H.; Fagerholm, N.; Bieling, C.; Bürgi, M.; Kizos, T.; Kuemmerle, T.; Primdahl, J.; Verburg, P.H. The Driving Forces of Landscape Change in Europe: A Systematic Review of the Evidence. *Land Use Policy* **2016**, *57*, 204–214. [CrossRef]
99. Daniel, T.C.; Muhar, A.; Arnberger, A.; Aznar, O.; Boyd, J.W.; Chan, K.M.A.; Costanza, R.; Elmqvist, T.; Flint, C.G.; Gobster, P.H.; et al. Contributions of Cultural Services to the Ecosystem Services Agenda. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 8812–8819. [CrossRef]
100. Vysna, V.; Maes, J.; Petersen, J.; La Notte, A.; Vallecillo, S.; Aizpurua, N.; Ivits, E.; Teller, A. *Accounting for Ecosystems and Their Services in the European Union (INCA)—Final Report from Phase II of the INCA Project Aiming to Develop a Pilot for an Integrated System of Ecosystem Accounts for the EU*, 2021st ed.; Publications Office: Luxembourg, 2020.
101. Schirpke, U.; Scolozzi, R.; De Marco, C. *B.4 -B9 Modello Dimostrativo di Valutazione Qualitativa e Quantitativa Dei Servizi Ecosistemici Nei Siti Pilota. Parte 1: Quantificazione dei Servizi Ecosistemici. Report del Progetto Making Good Natura (LIFE+11 ENV/IT/000168)*; EURAC Research: Bolzano, Italy, 2015; pp. 1–116. Available online: http://www.lifemgn-serviziecosistemici.eu/IT/docu/Pages/default.aspx.html (accessed on 9 March 2023).
102. Tardieu, L.; Roussel, S.; Thompson, J.D.; Labarraque, D.; Salles, J.M. Combining Direct and Indirect Impacts on Ecosystem Service Loss Associated with Infrastructure Construction. *J. Environ. Manag.* **2015**, *152*, 145–157. [CrossRef]
103. Grilli, G.; Nikodinoska, N.; Paletto, A.; De Meo, I. Stakeholders' Preferences and Economic Value of Forest Ecosystem Services: An Example in the Italian Alps. *Balt. For.* **2015**, *21*, 298–307.
104. Marta-Pedroso, C.; Laporta, L.; Gama, I.; Domingos, T. Economic Valuation and Mapping of Ecosystem Services in the Context of Protected Area Management (Natural Park of Serra de São Mamede, Portugal). *One Ecosyst.* **2018**, *3*, e26722. [CrossRef]
105. Bernetti, I.; Sottini, V.A.; Marinelli, N.; Marone, E.; Menghini, S.; Riccioli, F.; Sacchelli, S.; Marinelli, A. Quantification of the Total Economic Value of Forest Systems: Spatial Analysis Application to the Region of Tuscany (Italy). *Aestimum* **2013**, *62*, 29–65. [CrossRef]
106. Pettenella, D.; Marchetti, M.; Motta, R.; Vacchiano, G. Vaia Storm Facing the Unbearable Lightness of Forest Reporting. *Forest* **2021**, *18*, 1–4. [CrossRef]
107. Hein, L. Economic Benefits Generated by Protected Areas: The Case of the Hoge Veluwe Forest, the Netherlands. *Ecol. Soc.* **2011**, *16*, 13. [CrossRef]
108. White, C.; Dunscombe, R.; Dvarskas, A.; Eves, C.; Finisdore, J.; Kieboom, E.; Maclean, I.; Obst, C.; Rowcroft, P.; Silcock, P. *Developing Ecosystem Accounts for Protected Areas in England and Scotland: New Forest National Park Summary Report*; Department for Food, Environment & Rural Affairs: London, UK, 2015; pp. 1–34.
109. 109 Marchetti, M.; Motta, R.; Pettenella, D.; Sallustio, L.; Vacchiano, G. Forests and Forest-Wood System in Italy: Towards a New Strategy to Address Local and Global Challenges. *Forest* **2018**, *15*, 41–50. [CrossRef]
110. de Jong, R.; Edens, B.; van Leeuwen, N.; Schenau, S.; Remme, R.; Hein, L.; Remme, R. Ecosystem Accounting Limburg Province, the Netherlands. Part I: Physical Supply and Condition Accounts. 2016, pp. 1–26. Available online: https://www.wavespartnership.org/en/knowledge-center/ecosystem-accounting-limburg-province-netherlands-part-1-physical-supply-and (accessed on 9 March 2023).
111. Remme, R.; Hein, L. Ecosystem Accounting Limburg Province, The Netherlands. Part II: Monetary Supply and Use Accounts. 2016, pp. 1–26. Available online: https://www.wavespartnership.org/en/knowledge-center/ecosystem-accounting-limburg-province-netherlands-part-2-monetary-supply-and-use (accessed on 9 March 2023).
112. Cervelli, E.; Pindozzi, S.; Allevato, E.; Saulino, L.; Silvestro, R.; Scotto Di Perta, E.; Saracino, A. Landscape Planning Integrated Approaches to Support Post-Wildfire Restoration in Natural Protected Areas: The Vesuvius National Park Case Study. *Land* **2022**, *11*, 1024. [CrossRef]

113. Paletto, A.; Geitner, C.; Grilli, G.; Hastik, R.; Pastorella, F.; Garcìa, L.R. Mapping the Value of Ecosystem Services: A Case Study from the Austrian Alps. *Ann. For. Res.* **2015**, *58*, 157–175. [CrossRef]
114. Willis, K.G.; Garrod, G.; Scarpa, R.; Lovett, A.; Bateman, I.J.; Hanley, N.; Macmillan, D.C.; Commission, F. The Social and Environmental Benefits of Forests in Great Britain. *Soc. Environ. Benefits For. Phase 2* **2003**, 1–36. Available online: https://forestry.gov.scot/publications/665-the-social-and-environmental-benefits-of-forests-in-great-britain-main-report (accessed on 9 March 2023).
115. Xue, D.; Tisdell, C. Valuing Ecological Functions of Biodiversity in Changbaishan Mountain Biosphere Reserve in Northeast China. *Biodivers. Conserv.* **2001**, *10*, 467–481. [CrossRef]
116. Marino, D. *La Contabilità Ambientale Dei Servizi Ecosistemici Della Città Metropolitana Di Roma Capitale*; Unimol: Campobasso, Italy, 2023; ISBN 9788896394410.
117. Duarte, B.; Carreiras, J.; Caçador, I. Climate Change Impacts on Salt Marsh Blue Carbon, Nitrogen and Phosphorous Stocks and Ecosystem Services. *Appl. Sci.* **2021**, *11*, 1969. [CrossRef]
118. Esen, S.E.; Hein, L.; Cuceloglu, G. Accounting for the Water Related Ecosystem Services of Forests in the Southern Aegean Region of Turkey. *Ecol. Indic.* **2023**, *154*, 110553. [CrossRef]
119. Piaggio, M.; Siikamäki, J. The Value of Forest Water Purification Ecosystem Services in Costa Rica. *Sci. Total Environ.* **2021**, *789*, 147952. [CrossRef] [PubMed]
120. Mueller, M.; Pander, J.; Geist, J. The Ecological Value of Stream Restoration Measures: An Evaluation on Ecosystem and Target Species Scales. *Ecol. Eng.* **2014**, *62*, 129–139. [CrossRef]
121. de la Cruz, A.; Benedicto, J. Assessing Socio-Economic Benefits of Natura 2000—A Case Study on the Ecosystem Service Provided by SPA Pico Da Vara/Ribeira DO Guilherme. Output of the Project Financing Natura 2000: Cost Estimate And Benefits of Natura 2000 (Contract No.: 070307/2007/484403/MAR/B2). 2009, Volume 44. Available online: http://ec.europa.eu/environment/nature/natura2000/financing/docs/azores_case_study.pdf (accessed on 9 March 2023).
122. Matero, J.; Saastamoinen, O. In Search of Marginal Environmental Valuations—Ecosystem Services in Finnish Forest Accounting. *Ecol. Econ.* **2007**, *61*, 101–114. [CrossRef]
123. Mastrorilli, M.; Rana, G.; Verdiani, G.; Tedeschi, G.; Fumai, A.; Russo, G. Economic Evaluation of Hydrological Ecosystem Services in Mediterranean River Basins Applied to a Case Study in Southern Italy. *Water* **2018**, *10*, 241. [CrossRef]
124. Broadmeadow, S.; Thomas, H.; Nisbet, T.; Valatin, G.; Nisbet, T.; Valatin, G. Valuing flood regulation services of existing forest cover to inform natural capital accounts. *For. Res. Alice Holt Lodg. Farnham Surrey* **2018**, 1–28. Available online: https://www.forestresearch.gov.uk/publications/valuing-flood-regulation-services-of-existing-forest-cover-to-inform-natural-capital-accounts/ (accessed on 9 March 2023).

land

MDPI

Article

Spatial Trade-Offs and Synergies between Ecosystem Services in Guangdong Province, China

Qian Xu [1], Ying Yang [2,*], Ren Yang [3], Li-Si Zha [1], Zi-Qing Lin [1] and Shu-Hao Shang [1]

1 School of Public Administration, Guangdong University of Finance & Economics, Guangzhou 510320, China; xuqian@gdufe.edu.cn (Q.X.); 20171026@gdufe.edu.cn (L.-S.Z.); ziqinglin@student.gdufe.edu.cn (Z.-Q.L.); shangshuhao@student.gdufe.edu.cn (S.-H.S.)
2 School of Culture Tourism and Geography, Guangdong University of Finance & Economics, Guangzhou 510320, China
3 School of Geography and Planning, Sun Yat-sen University, Guangzhou 510275, China; yangren666@mail.sysu.edu.cn
* Correspondence: yangyingmail@gdufe.edu.cn

Abstract: The trade-offs between ecosystem services directly affect the quality of the ecological environment and the survival and development of human society, which is of great concern to academia, governments, and non-governmental organizations. Guangdong Province is a strong economic performer in China; hence, we selected it to explore the trade-off and synergy differences between different ecosystem services, and to investigate the mechanisms of their influence in economically developed regions with a large population density. Our results showed three main points: (1) The ecosystem services in Guangdong Province showed clear spatial heterogeneity. In addition, northern Guangdong has high levels of water retention, with a value of 5804.73×10^4 m^3/km^2 and high values for carbon sequestration and soil retention. Western Guangdong is a functional area for food production, and the Pearl River Delta is an economically developed region with low levels of ecosystem services. (2) Overall, in Guangdong Province, three pairs of ecosystem services, namely water retention–soil retention, carbon sequestration–water retention, and carbon sequestration–soil retention, showed a strong positive correlation and good synergistic relationships. The other three pairs of relationships show strong trade-off effects. (3) The relationships between similar ecosystem services show completely different characteristics in different regions. Carbon sequestration and water retention, carbon sequestration and biodiversity conservation, water retention and biodiversity conservation, and soil retention and biodiversity conservation were mainly manifested in high–high synergies, particularly in northern Guangdong; carbon sequestration and soil retention and water retention and soil retention, primarily manifested synergies; carbon sequestration and food production, water retention and food production, and soil retention and food production mainly manifested as trade-off relationships.

Keywords: ecosystem services; trade-off; synergy; spatial relation

Citation: Xu, Q.; Yang, Y.; Yang, R.; Zha, L.-S.; Lin, Z.-Q.; Shang, S.-H. Spatial Trade-Offs and Synergies between Ecosystem Services in Guangdong Province, China. *Land* **2024**, *13*, 32. https://doi.org/10.3390/land13010032

Academic Editors: Luca Battisti, Fabrizio Aimar and Federico Cuomo

Received: 24 November 2023
Revised: 13 December 2023
Accepted: 20 December 2023
Published: 26 December 2023

1. Introduction

Ecosystem services are the environmental conditions and the effects of ecosystem formation and maintenance on human survival and development [1]. However, ecosystem services do not exist or develop independently. Complex reciprocal relationships exist among various services within an ecosystem and among several ecosystems [2]. These interactions mainly manifest as trade-offs between waning and waxing or synergies for mutual gains. Diverse and complex ecological environments provide various services for human well-being, and the impact of human activities is often at the expense of certain service levels [3]. In economically developed areas, the contradiction between intense human activities and the ecological environment is more prominent, complicating the trade-off and synergistic relationships between ecosystem services. The trade-offs between different services and the factors influencing them must be analyzed because they affect the level of ecosystem services and the stability and development of the whole ecosystem [4,5]. Therefore, Guangdong Province, being a province with strong economic performance in China, was selected as the research area; this area is also highly significant to the study of spatial trade-offs, synergistic relationships, and the mechanisms influencing regional ecosystem services.

Trade-offs in ecosystem services are mainly generated by human demand preferences. When people consume certain ecosystem services, they will have an impact on other ecosystem services, intentionally or unintentionally, leading to trade-offs and synergies between ecosystem services [6,7]. A scientific understanding of the functional characteristics, manifestations, driving mechanisms, and scale effects of ecosystem service trade-offs/synergies is of great significance for improving human well-being and achieving a "win-win" situation between human society and the ecosystem [8]. A comprehensive understanding of the relationships between ecosystem services includes multiple dimensions, such as trade-offs, synergies, and compatibilities [9]. A trade-off is a negative relationship in which ecosystem services are restricted by other functions, such as ebb and flow, including supporting and regulating functions [10,11]. A synergy is a positive relationship, and several ecosystem services show symbiosis, enhancing or weakening together, such as support and cultural functions, and regulatory and cultural functions [12]. Compatibility shows no significant relationship between ecosystem services [13]. In reality, in order to improve a certain ecosystem service, we often inevitably affect trade-offs and synergies with other services [14]. Scholars have conducted extensive research on the interaction between ecosystem services and concluded that trade-offs and synergies between ecosystem services are universal [15,16]. Ecosystem services are influenced by various factors such as land use and cover change, human needs, parameter selection, regional differences, and imbalances [17]. Different regions show significant differences [18,19]. To achieve the harmonious development of humans and nature in an urban system, we have integrated ecological elements into urban planning [20,21]. The correlation between ecosystem services and urban green infrastructure/urban sprawl currently play an important role in spatial planning [22]; however, studies on these aspects are still limited.

Ecosystem services are mainly divided into four types: provisioning (food, water, wood, and fuel), regulating (climate, flood, and disease regulation; water purification), cultural (aesthetic, spiritual, educational, and recreational), and support services that are necessary to maintain other types of services (nutrient cycling, soil formation) [23,24]. These services provide personal security, security from disasters, access to resources, food, shelter, adequate livelihoods, health, good social relations—i.e., social cohesion. For different areas (urban, rural, or wild), the types of ecosystem services concerned are different. Research often focuses on the key service types in the region. The main evaluation methods for ecosystem services are index evaluation, value evaluation, and model simulation (including models UFORE, SolVES, BUGS, ARIES, InVest, EPM, InFOREST, Envision, and EcoMetrix). These methods are widely used globally [25]. Common research methods for identifying ecosystem service trade-offs/synergies include correlation analysis, principal component analysis, root mean square deviation, and bivariate spatial autocorrelation [26,27]. At present, many models have been developed to identify the interrelationships between ecosystem services, such as InVEST, ARIES, ESValue, EcoAIM, EcoMetrix, NAIS, and SolVES [28,29]. Scholars have reported differences in the quantity of regional ecosystem services recorded using different measurement methods and the nature and intensity of ecosystem service relationships. For example, the SolVES model requires social questionnaire survey data, and the questionnaire quality directly affects the evaluation results. The UFORE, SolVES, and BUGS models have limitations regarding the spatial scale of the study area. Remote sensing data are applicable to the evaluation of ecosystem services at different spatial scales, but their accuracy is difficult to guarantee. Therefore, selecting the appropriate method for evaluating the relationships between regional ecosystem services is important to ensure accurate results.

Most developing countries in an important period of economic development often pay attention to promoting economic benefits while ignoring ecological benefits. Therefore, the ultimate goal of ecosystem service research should be to maximize the comprehensive benefits of the human–earth system, ease the trade-offs between different ecosystem services, and improve human welfare [30,31]. As an important developing country, China is currently in a crucial transition period from high-speed to high-quality economic development. Therefore, urban economic development should be coordinated with environmental protection. Guangdong, a relatively developed province in China, was selected as the research area in this study. This study clarifies the main types of ecosystem services and their spatial differentiation characteristics. The study focuses on analyzing the trade-offs and synergies among different ecosystem services and the differences in their degrees of influence, as well as comparing and analyzing their spatial patterns. Then, the influence mechanisms of trade-offs and synergies between ecosystem services were analyzed and areas for improvement were determined. The findings of this study are of great significance for the improvement of regional eco-environmental carrying capacity, protection, and management, the creation of solutions for sustainable development goals, and the coordination between economic development and ecological protection.

2. Study Area and Methods

2.1. Study Area

Guangdong Province is located in the southernmost part of mainland China, with a land area of 179,800 km^2. It is located between 20°13′ N–25°31′ N and 109°39′ E–117°19′ E and faces the South China Sea in the south. Guangdong Province has jurisdiction over 21 prefecture-level cities (including two sub-provincial cities), which are divided into four regions: the Pearl River Delta, Eastern Guangdong, Western Guangdong, and northern Guangdong. The Pearl River Delta includes the cities of Guangzhou, Shenzhen, Foshan, Dongguan, Zhongshan, Zhuhai, Jiangmen, Zhaoqing and Huizhou; Eastern Guangdong includes Shantou, Chaozhou, Jieyang, and Shanwei; Western Guangdong includes Zhanjiang, Maoming, Yangjiang, and Yunfu; and northern Guangdong includes Shaoguan, Qingyuan, Meizhou, and Heyuan (Figure 1).

Guangdong Province is located in the tropical and subtropical regions, with the Tropic of Cancer running through its central part. It is located on the north coast of the South China Sea, is heat rich, has abundant rainfall, a wide variety of animals and plants, and good natural conditions. Guangdong Province is rich in forest resources, with a forest area of 107,925.33 km^2 as of 2019, accounting for 60.05% of the total area of major land types in the province, including arbor, bamboo, and shrub forests. Guangdong Province has complex and diverse landforms, with hills, platforms, and basins developing between the mountains. The soil types are diverse, and the zonal distribution is obvious. Zonal soil types are red, latosolic red, and lateritic soils from north to south and include a small amount of yellow soil and yellow brown soil. Non-zonal soil types include paddy, tidal, mountain meadow, lime, and purple soils. The province belongs to the East Asian monsoon region, and has middle subtropical, southern subtropical, and tropical climates from north to south. It is also one of the provinces with the most abundant light, heat, and water in China. The average sunshine duration of the whole province is 1745.8 h. The average annual temperature is 22.3 °C. The average annual precipitation ranges from 1300 to 2500 mm. The spatial distribution of rainfall shows a high trend in the south and low in the north. Guangdong Province is rich in water resources, with a total water resource amount of 2068.2 × 10^8 m^3 in 2019. There are numerous rivers, mainly in the Pearl River Basin, the Hanjiang River basin that only flows into the sea, and the rivers along the east and west coasts. There are 60 branches and tributaries at all levels with a catchment area of more than 1000 km^2.

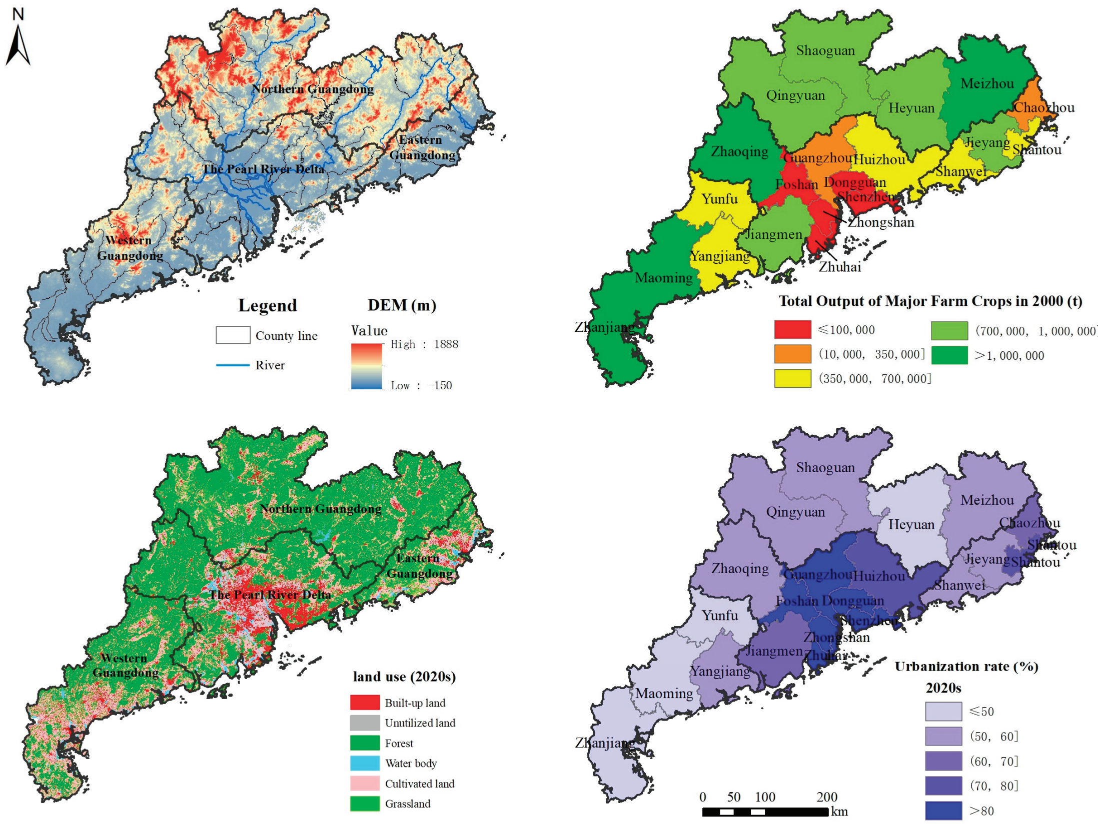

Figure 1. Location of the study area.

Guangdong is China's most populous province, with a population of 126 million in 2020. The population density is 702.77 people /km^2, and the urbanization rate is 74.15%, but regional differences are large (Table 1). Furthermore, since 1989, Guangdong's gross domestic product (GDP) has continuously ranked first in China, and it has become the province with the largest economy in the country, accounting for 1/8 of the country's total economic aggregate. In 2020, Guangdong's GDP reached 11,076.09 billion yuan, while the Pearl River Delta core region's GDP accounted for 80.83% of that of the whole province.

Table 1. Basic socioeconomic characteristics of Guangdong Province in 2020.

Region	Area/10^3 × km^2	Population/Million	Population Density People/km^2	Urbanization Rate/%	Gross Domestic Product/100 Million Yuan
Pearl River Delta	54.91	78.24	14.25	87.24	89,523.93
Eastern Guangdong	15.49	16.32	10.54	60.6	7053.51
Western Guangdong	32.67	15.77	4.83	46.15	7739.97
Northern Guangdong	76.74	15.92	2.07	51.62	6443.54
Guangdong Province	179.81	126.25	7.02	74.15	110,760.9

2.2. Methodology

2.2.1. Measurement of Ecosystem Services

Considering the natural background and socioeconomic conditions of Guangdong Province and referring to the "Territorial Spatial Planning of Guangdong Province" and other relevant planning and policy documents, five kinds of ecosystem services were selected for analysis: carbon sequestration, water retention, soil retention, food production, and biodiversity conservation.

This study used ecosystem services data from the Chinese Academy of Sciences Ecological Environmental Research Center (http://www.sciencedb.cn/dataSet/handle/458, accessed on 31 December 2018). The dataset is based on remote sensing feature classification data. The management modes of land features, community structure, and ecological process differences were analyzed using MODIS satellite data Q13A1 [32,33]. Temperature and precipitation data were provided by the China Meteorological Data Sharing Network (https://data.cma.cn/data/detail/dataCode/A.0012.0001.html, accessed on 5 January 2017) and topographic data, from the United States' GEOM satellite. Ecosystem services in China in 2010 were simulated based on ecological process simulation methods, such as the CASA light energy utilization rate model, the universal soil loss equation, the water balance equation, the wind model, and by summarizing the literature and ground monitoring data to determine model parameters. A spatial dataset with a resolution of 250 m was created.

Carbon sequestration was measured mainly based on net primary productivity (NPP), which is represented by the product of photosynthetic active radiation absorbed by plants and actual light utilization (ε). Water retention was calculated using the water balance equation. Soil retention was simulated using the general soil loss equation. In the specific calculation, existing measured soil erosion data was used to verify the model simulation results and modify the parameters. Food production data provided county ecosystems with food output, such as grain, aquatic products, meat, forest fruit products, uniformly converted into energy. Also, rather than using the total number of species, the measure of biodiversity conservation used in this study represented the total number of indicator species with a recorded distribution in each county, primarily nationally protected plants and animals of special significance, or species with threatened or endangered status. The biodiversity conservation values in Guangdong Province were the average values for all districts and counties, and the values of the four regions were the average values of all districts and counties in the region.

2.2.2. Evaluation of Ecosystem Service Trade-Offs and Synergies

The Pearson correlation coefficient method was used to evaluate ecosystem service trade-offs and synergies. If the correlation coefficient was positive, the synergies between the two services were mutually promoted. Conversely, a negative correlation coefficient indicated a trade-off between the two services. Otherwise, the two functions were independent of each other [24].

In terms of the spatial dimension, a bivariate local spatial autocorrelation model was used to quantitatively measure the spatial distribution pattern and correlation characteristics of ecosystem service trade-offs and synergies in Guangdong Province. Cluster diagrams between the pairs of ecosystem services in the study area were obtained through bivariate local Moran's I spatial analysis using GeoDa (v1.20) software. In this study, a queen spatial adjacency matrix was constructed to measure the statistics of the local indicator of spatial association between two services. Specifically, "high-high" (HH) indicated that the two services with a high score clustered significantly in this region, "low-low" (LL) indicated that the two services with a low score clustered significantly in this region, "high-low" (HL) indicated that the first function scores were high and that the other function scores were low, and "low-high" (LH) indicated the opposite of HL. "Not significant" indicated that the two functions were independent within the regional space. HH and LL were regarded as synergies, whereas HL and LH were regarded as trade-offs. The values of local Moran's I were processed without dimensionality and ranged from 0 to 1.

2.2.3. Degree of Influence of Ecosystem Service Trade-Offs and Synergies

To classify the degree of ecosystem service trade-offs and synergies, a specific method was applied. First, the natural breakpoint method was used to divide the five ecosystem services into three levels: low, medium, and high, numbered 1, 2, and 3, respectively (Table 2).

Table 2. Classification levels of ecosystem service capacity.

Server Type	Low (1)	Medium (2)	High (3)
Carbon sequestration (t/km^2)	[0, 65]	(65, 204)	>204
Water retention (10^4 m/km^2)	[0, 32]	(32, 81)	>81
Biodiversity conservation (numbers)	[0, 78]	(78, 92)	>92
Food production (10^8 $kcal/km^2$)	[0, 4]	(4, 9)	>9
Soil retention (10^4 t/km^2)	[0, 9]	(9, 28)	>28

The five types of service standardization and classification of raster data were superimposed using ArcGIS 10.2 data:

$$CODE = C \times 10{,}000 + W \times 1000 + B \times 100 + F \times 10 + S \quad (1)$$

In Equation (1), C, W, B, F, and S represent carbon sequestration, water retention, biodiversity conservation, food production, and soil retention, respectively. CODE is a five-digit code, and each code sequence is a combination of 1, 2, and 3, representing the degree of influence of the ecosystem services [34].

Subsequently, criteria for classifying trade-offs and synergies were developed (Table 2). Trade-offs were classified as strong or weak. A strong trade-off was a state with one high service supply capacity, and all others were medium or low. Service capacity combinations in a strong trade-off may be 1 high 4 low, 1 high 1 medium 3 low, 1 high 2 medium 2 low, etc. A weak trade-off referred to a state with two, three, or four types of high service capacities, while all other services had medium or low capacities. Service capacity combinations in a weak trade-off may be 2 high 3 low, 2 high 1 medium 2 low, 2 high 2 medium 1 low, etc. Synergies were also classified as high or low. In high synergies, all services were high; this being the most coordinated state and the ultimate goal of ecosystem management. High-synergy combinations include 5 high, 4 high 1 medium, 3 high 2 medium, etc. A low synergy meant that all five types of service capacities were at a low level, which is the least ideal state. Low-synergy combinations included 1 medium 4 low, 2 medium 3 low, and 3 medium 2 low.

3. Results

3.1. Spatial Differentiation of Ecosystem Services in Guangdong Province

To ensure that different ecosystem services were comparable (Table 3), ecosystem service values were processed without dimensionality, and all values ranged from 0 to 1 (Table 4). Among the five ecosystem services in Guangdong Province, water retention was the strongest (0.71). Soil retention and carbon sequestration had values of 0.54 and 0.51, respectively. Biodiversity conservation (0.48) and food production (0.33) were ranked fourth and fifth, respectively, among the ecosystem services.

Specifically, the spatial distribution of the different ecosystem services was as follows:

(1) The overall carbon sequestration level in Guangdong Province was 50.06 t/km^2, and its spatial distribution was higher in the north than in the south. The overall carbon sequestration level in the Pearl River Delta region (47.58 t/km^2) was higher than that in Western Guangdong (39.79 t/km^2) and Eastern Guangdong (40.77 t/km^2). However, there was a contiguous low-value area in the Pearl River estuary (Figure 2). The contiguous low-value area on the west bank of the Pearl River estuary was larger than that on the east bank.

The cities of Dongguan, Zhongshan, and Foshan had the lowest carbon sequestration levels in Pearl River Delta, with 13.89 t/km^2, 17.61 t/km^2, and 19.06 t/km^2, respectively. The carbon sequestration level in Zhaoqing City in the Pearl River Delta was the highest of the entire province with 66.24 t/km^2. The carbon sequestration level of Western Guangdong was the lowest among the four regions in the province, especially in the Leizhou Peninsula, the southernmost part of mainland China, with only 13.35 t/km^2 for the 21 cities in the province. The carbon sequestration level in Shantou City in Eastern Guangdong was also noticeably low with 18.59 t/km^2, lower than that of the surrounding cities. Northern Guangdong showed a remarkably high carbon sequestration, and the four cities in the region had values greater than 55 t/km^2. The maximum carbon sequestration value of the entire province (1164 t/km^2) was also distributed in Heyuan City in northern Guangdong Province.

Table 3. Values of ecosystem services in Guangdong Province in China in 2010.

	Carbon Sequestration (t/km^2)	**Water Retention (10^4 m/km^2)**	**Soil Retention (10^4 t/km^2)**	**Food Production (10^8 kcal/km^2)**	**Biodiversity (Numbers)**
Pearl River Delta	47.58	51.20	7.76	3.05	77
Northern Guangdong	59.91	58.05	9.26	2.08	87
Eastern Guangdong	40.77	38.58	7.59	4.53	75
Western Guangdong	39.79	49.52	6.75	6.80	76
Guangdong Province	50.06	52.40	8.11	3.63	80

Table 4. Values without dimensionality of ecosystem services in Guangdong Province in China in 2010.

	Carbon Sequestration	**Water Retention**	**Soil Retention**	**Food Production**	**Biodiversity**
Pearl River Delta	0.39	0.65	0.40	0.21	0.22
Northern Guangdong	1.00	1.00	1.00	0.00	1.00
Eastern Guangdong	0.05	0.00	0.33	0.52	0.00
Western Guangdong	0.00	0.56	0.00	1.00	0.11
Guangdong Province	0.51	0.71	0.54	0.33	0.48

(2) Guangdong has a humid climate, high forest coverage, and strong water retention for ecosystem services. The average value of water retention in Guangdong was 52.40×10^4 m^3/km^2, and the spatial distribution among cities was similar to that of carbon sequestration. Northern Guangdong was also a high-value area for water retention, with a value of 58.05×10^4 m^3/km^2. Except for Meizhou, the water retention in the other three cities was higher than the average provincial level. This is followed by the Pearl River Delta and Western Guangdong regions. The high-value areas in the Pearl River Delta region were distributed in its periphery. Remarkably, among the 21 cities, Yangjiang (74.10×10^4 m^3/km^2) and Zhanjiang (18.16×10^4 m^3/km^2) had the highest and lowest water conservation values in Western Guangdong, respectively. Water conservation in Eastern Guangdong (38.58×10^4 m^3/km^2) was significantly lower than in other regions.

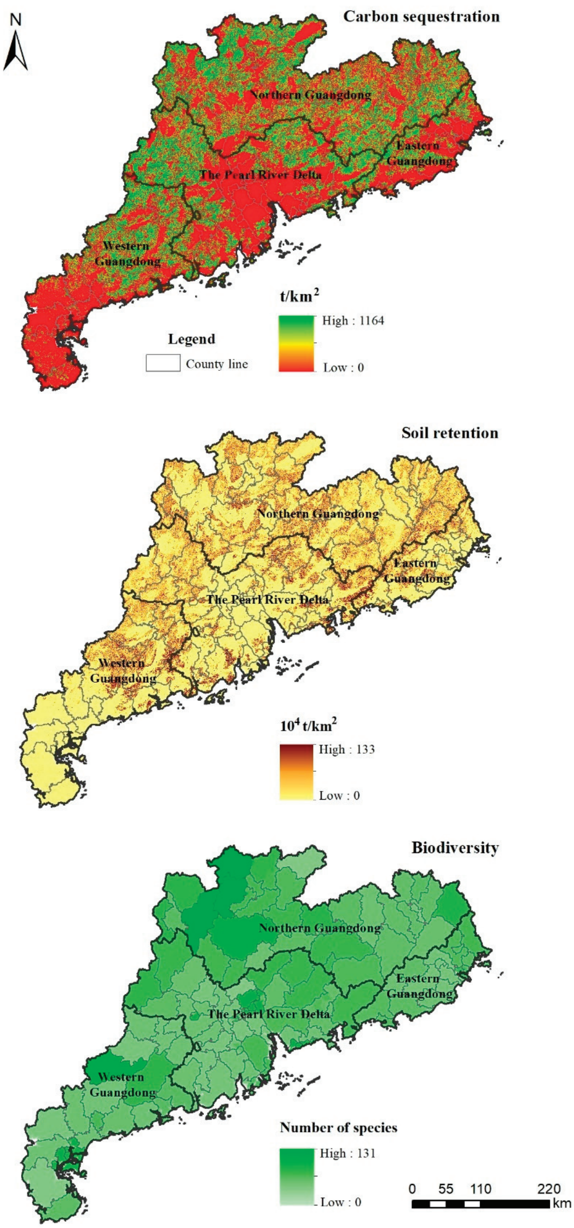

Figure 2. Spatial distribution of ecosystem services in Guangdong Province in 2010.

(3) Guangdong Province had a strong soil retention service, with an average value of 8.11 × 10^4 m^3/km^2. The soil retention level of northern Guangdong, which has a high forest coverage, was the highest, with a value of 9.26 × 10^4 m^3/km^2. Soil retention services in the Pearl River Delta and Eastern Guangdong regions were similar, with 7.76 × 10^4 m^3/km^2 and 7.59 × 104 m^3/km^2, respectively, among which Huizhou had the highest of the 21 cities with 10.96 × 10^4 m^3/km^2. Western Guangdong had the lowest soil retention service value with 6.75 × 10^4 m^3/km^2. In this region, Zhanjiang had the lowest soil retention value among the

21 cities in the Leizhou Peninsula with 0.88 × 10^4 m^3/km^2, while Yunfu and Yangjiang had strong soil retention with values of 10.69 × 10^4 m^3/km^2 and 10.09 × 10^4 m^3/km^2, respectively.

(4) Food production data were sourced from county data, and foods such as grain, aquatic products, meat, and fruits were uniformly converted into total food supply calories. The average value of food production in Guangdong Province was 3.63 × 10^8 kcal/km^2, and the main food production area was mainly concentrated in Western Guangdong, with a value of 6.80 × 10^8 kcal/km^2. In this region, the cities of Zhanjiang and Maoming had the highest food production values with 10.65 × 10^8 kcal/km^2, and 7.08 × 10^8 kcal/km^2, respectively. This was followed by Eastern Guangdong and the Pearl River Delta, with values of 4.53 × 10^8 kcal/km^2 and 3.05 × 10^8 kcal/km^2, respectively. In Eastern Guangdong, Shantou City had the highest food production value with 8.34 × 10^8 kcal/km^2, followed by Jieyang City with 5.09 × 10^8 kcal/km^2. The cities of Chaozhou and Shanwei did not reach provincial average levels. In the Pearl River Delta region, food production in Guangzhou and Jiangmen was relatively high, while very low in Shenzhen and Dongguan with only 0.03 × 10^8 kcal/km^2 and 0.08 × 10^8 kcal/km^2, respectively. However, the food production in northern Guangdong was the lowest with only 2.08 × 10^8 kcal/km^2, less than one third of that in Western Guangdong. Northern Guangdong is an important ecological barrier in Guangdong Province with extensive forest land and a low proportion of cultivated land; thus, food production is not its main ecosystem service.

(5) Guangdong Province has a complex ecological environment and a rich biodiversity. The biodiversity conservation value in Guangdong Province was 80 and, among the four regions, the biodiversity maintained in northern Guangdong was the highest at 86. This is to be expected as important forest areas, nature reserves, and natural parks in Guangdong are mostly distributed in northern Guangdong. In fact, Shimentai Nature Reserve, the largest contiguous forest reserve in Guangdong Province, is located in the southernmost part of the Nanling Mountains in northern Guangdong. The main objects of protection are subtropical evergreen broad-leaved forests, rare plants, and animals. There are 2242 species of higher plants and 301 wild vertebrate species in Shimentai Nature Reserve. Among them, one species of first-class nationally protected plant and 23 of second-class were included in the study. There were four species in the category first-class national protected animals and 41 under second-class protection. Among all the districts and counties, Ruyuan County (131) and Lechang County (117) in Shaoguan City and Fogang County (114) in Qingyuan City had the highest biodiversity. The lowest number of indicator species were conserved in Eastern Guangdong with 74.

3.2. Ecosystem Service Trade-Offs and Synergies, and Their Influence in Guangdong Province

The correlation between paired services among the five ecosystem services was obtained based on Pearson correlation analysis (Figure 3). Water retention–soil retention, carbon sequestration–water retention, and carbon sequestration–soil retention showed positive correlations (r = 0.389, r = 0.299, r = 0.258, $p < 0.05$), indicating a synergistic relationship between them. These three ecosystem services are also the main functions of forestland. The correlation coefficients between carbon sequestration–biodiversity conservation, water retention–biodiversity conservation, and soil retention–biodiversity conservation were positive and statistically significant; however, the relative coefficient values were small (r = 0.073, r = 0.137, r = 0.116), indicating a poor synergistic relationship. The negative correlation between food production and carbon sequestration was low (r = −0.110, $p < 0.05$), indicating a weak trade-off effect. There were negative correlations between food production–water retention, food production–soil retention, and food production–biodiversity conservation (r = −0.179, r = −0.182, r = −0.304, $p < 0.05$), indicating trade-off effects and reciprocal relationships between them.

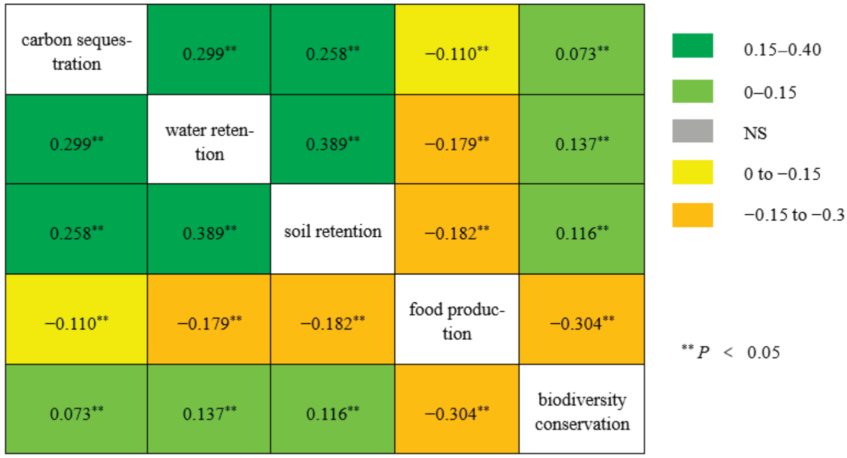

Figure 3. Pearson correlation coefficients between ecosystem service pairs.

Ecosystem services were divided into levels 1, 2, and 3 according to Table 1, and then the strengths and weaknesses of trade-offs and synergies between different services were evaluated. Also, the spatial distribution of ecosystem service trade-offs and synergies in Guangdong Province were assessed (Figure 4). This mainly showed poor synergies and strong trade-offs, accounting for 89.34% of the total area of Guangdong Province. Among them, poor synergies between different ecosystem service pairs occupied the largest area, mainly concentrated in Eastern Guangdong and most of the Pearl River Delta region. The other counties and districts in northern Guangdong showed poor synergies, except for Lechang County and Ruyuan Yao Autonomous County in Shaoguan City, and Yingde County and Yangshan County in Qingyuan City. There were also many regions with strong trade-offs between different ecosystem service pairs, mainly in Western and northern Guangdong and Guangzhou City in the Pearl River Delta region. The spatial distribution of the services with weak trade-offs was limited to Xinyi County in Maoming City in Western Guangdong, and Yingde County, Yangshan County, and Ruyuan Yao Autonomous County in Qingyuan City in northern Guangdong. Few areas with good synergies were scattered in Xinyi County in Maoming City in Western Guangdong.

From the combinations of ecosystem service trade-offs and synergies (Table 5), the trade-offs between services accounted for 44.33% of the total province area, and the strong trade-offs accounted for 34.15%, which was mainly manifested as services with levels of "1 high, 1 medium, 3 low", especially the 13,121 type (low carbon sequestration, high water retention, low biodiversity conservation, medium food production, and low soil retention), occupying an area of 4688.845 km^2. Weak trade-offs accounted for 10.18% of the whole province area, mainly showing combinations of "2 high, 1 medium, 2 low", "2 high, 2 medium, 1 low", and "2 high, 3 low", which covered an area of more than 1000 km^2. These combinations included 13,113 (low carbon sequestration, high water retention, low biodiversity conservation, low food production, high soil retention; 2367.10 km^2), 13,312 (low carbon sequestration, high water retention, high biodiversity conservation, low food production, medium soil retention; 1245.93 km^2), 13,213 (low carbon sequestration, high water retention, medium biodiversity conservation, low food production, high soil retention; 1179.34 km^2), 23,113 (medium carbon sequestration, high water retention, low biodiversity conservation, low food production, high soil retention; 1083.80 km^2), and 23,312 (medium carbon sequestration, high water retention, high biodiversity conservation, low food production, medium soil retention; 1018.74 km^2).

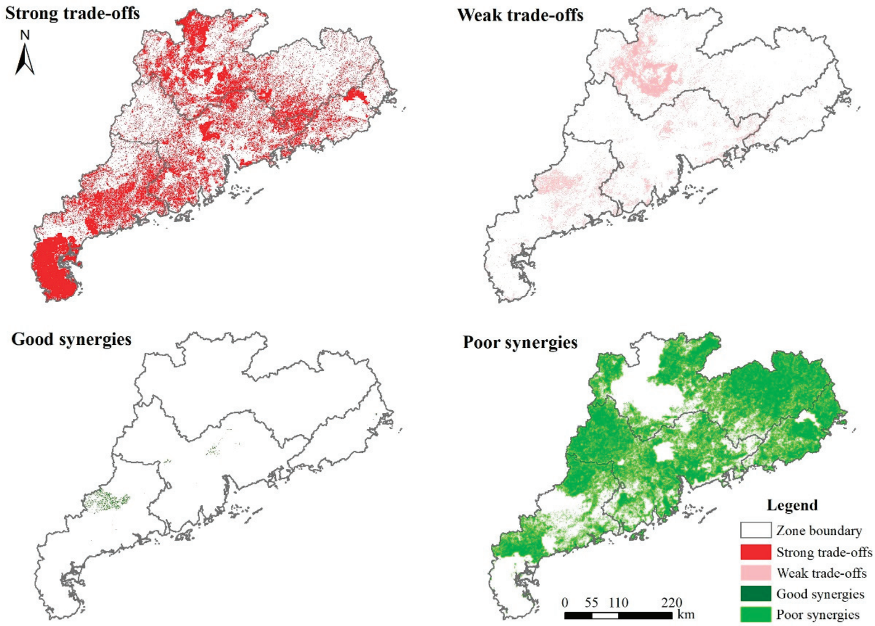

Figure 4. Spatial distribution of trade-offs (strong or weak) and synergies (good or poor) between ecosystem services.

Table 5. Classification criteria and statistics of trade-offs and synergies between the five ecosystem services.

Service Relationship	Area Ratio	Subclass	Area Ratio	Service Composition	Area Ratio
Trade-offs	44.33%	Strong trade-offs	34.15%	1 high 4 low	8.75%
				1 high 1 medium 3 low	12.71%
				1 high 2 medium 2 low	9.20%
				1 high 3 medium 1 low	3.49%
		Weak trade-offs	10.18	2 high 3 low	2.38%
				2 high 1 medium 2 low	4.32%
				2 high 2 medium 1 low	2.46%
				3 high 2 low	0.45%
				3 high 1 medium 1 low	0.54%
				4 high 1 low	0.03%
Synergies	55.67%	Good synergies	0.48%	5 high	0
				4 high 1 medium	0.01%
				3 high 2 medium	0.11%
				2 high 3 medium	0.26%
				1 high 4 medium	0.10%
		Poor synergies	55.19%	5 medium	0.01%
				1 medium 4 low	21.24%
				2 medium 3 low	12.97%
				3 medium 2 low	9.10%
				4 medium 1 low	2.53%
				5 low	9.36%

Poor synergistic relationships between different ecosystem service pairs accounted for 55.19% of the total area, mainly with the combinations “1 medium, 4 low” (21.24%) and “2 medium, 3 low” (12.97%). Here, the three specific combinations accounting for the largest area were 11,111 (low carbon sequestration, low water retention, low biodiversity conservation, low food production, low soil retention; 16,581.04 km^2), 11,112 (low carbon sequestration, low water retention, low biodiversity conservation, low food production, medium soil retention; 15,747.79 km^2), and 11,121 (low carbon sequestration, low water retention, low biodiversity conservation, medium food production, low soil retention; 11,942.03 km^2). Areas with good synergies accounted for only 0.48% of total provincial area.

3.3. Spatial Pattern Characteristics of Ecosystem Service Trade-Offs and Synergies in Guangdong Province

The spatial distribution characteristics and rules of the trade-offs and synergies between ecosystem services pairs were explored. Based on the area of Guangdong Province, fishnet (9 km) was selected and bivariate local Moran's I spatial analysis was performed based on the GeoDa (v1.20) software to obtain a cluster diagram between the ecosystem services in the study area (Figure 5) and explore the spatial distribution characteristics and rules of the tradeoff and synergistic relationships between the ecosystem services in the study area. In particular, HH synergies and LL synergies were mainly observed between carbon sequestration and water retention. HH synergies were mainly concentrated in areas rich in forest resources and were spatially manifested in Shaoguan, Qingyuan, and Heyuan cities in northern Guangdong, and Maoming and Yangjiang cities in western Guangdong. Carbon sequestration and water retention were the main ecosystem services of forest land. The Pearl River estuary coastal area with a developed economy and low forest coverage was mainly categorized as an LL synergy area. In addition, areas of cultivated land in Zhanjiang City, Shantou, and Shanwei City were categorized as LL synergistic areas.

Carbon sequestration and biodiversity conservation were mainly manifested in HH synergies, particularly in northern Guangdong and Maoming City in western Guangdong; a small number of LH trade-offs were mixed in with the HH synergy regions. The LL synergies were distributed in the coastal area, wherein HL trade-off zones and their mixed distribution was also detected.

Carbon sequestration and soil retention, and water retention and soil retention, show similar relationships, mainly for synergies. The forest land concentration areas in Maoming, Yunfu, Zhaoqing, Qingyuan, Heyuan, and Meizhou City formed continuous zonal HH synergies, whereas the cultivated land concentration areas in Zhanjiang, Shantou, and Shanwei showed LL synergies.

Carbon sequestration and food production, water retention and food production, and soil retention and food production are three pairs of services with similar relationship characteristics, and they mainly manifest as a trade-off relationship. HL trade-offs were concentrated in northern Guangdong and LH trade-offs were manifested in Zhanjiang City and Shantou City. LL synergies were mainly distributed in Zhongshan and Shenzhen City along the Pearl River estuary and in scattered areas in northern Guangdong; southeast Maoming was a contiguous HH coordination area.

The characteristics of water retention and biodiversity conservation and soil retention and biodiversity conservation were similar, mainly manifesting as synergies. Among them, HH synergies were mainly concentrated in northern Guangdong and those of water retention and biodiversity conservation were larger, whereas the LH trade-off area was also mixed in northern Guangdong.

Food production and biodiversity conservation mainly showed LH trade-off areas, which were mainly distributed in Shaoguan, Qingyuan, and Huizhou City. The distribution of HL trade-offs and LL synergies was lower, being limited to the coastal line of southern Guangdong Province.

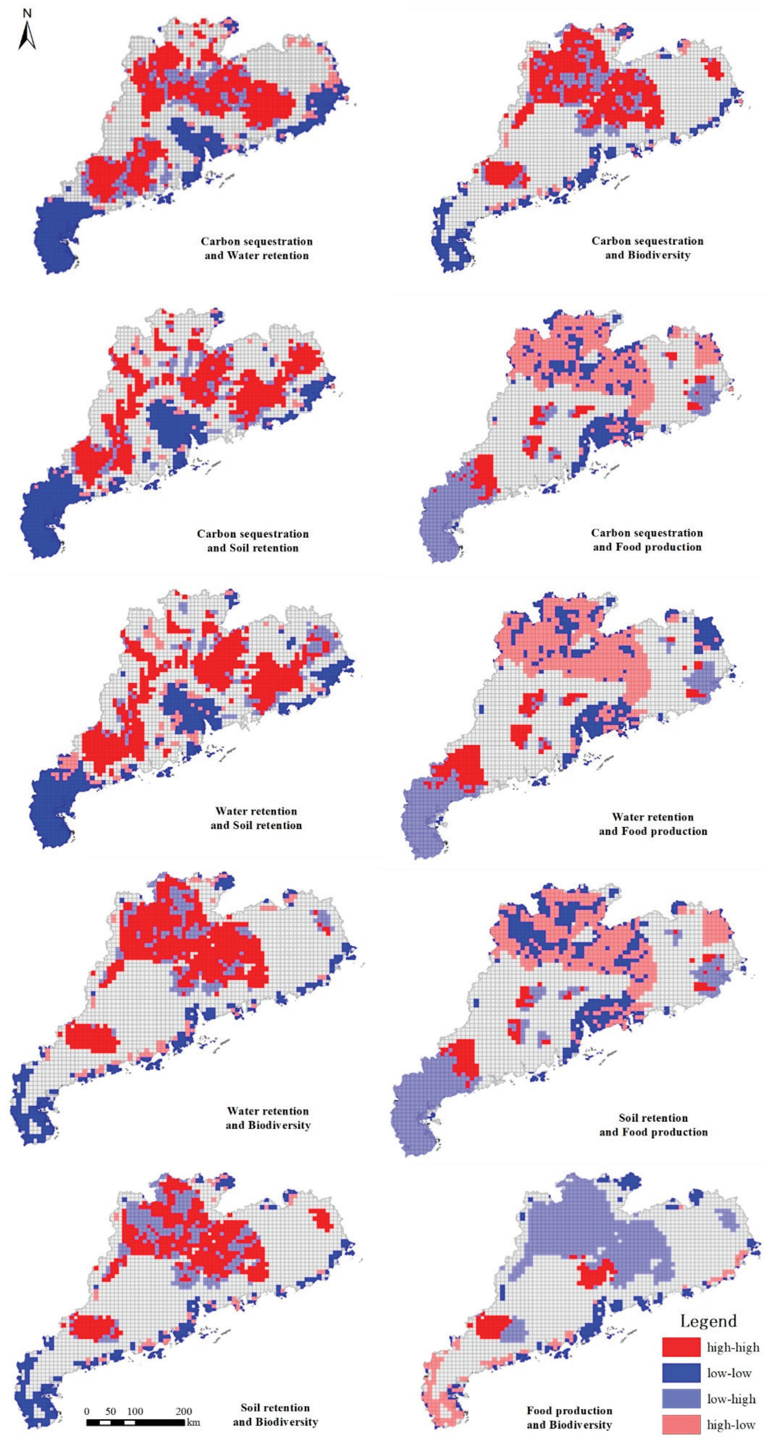

Figure 5. Spatial distribution of trade-offs and synergies between ecosystem services in Guangdong Province.

4. Discussion

4.1. Analysis of Spatial Diversity Mechanisms of Ecosystem Services

Owing to the influence of different natural and socioeconomic conditions, different ecosystem services in Guangdong Province showed clear spatial differences. Guangdong has a strong economy. In 2022, China's economic aggregate reached 121.02 trillion yuan, and Guangdong's GDP was the highest in the country (Guangdong has ranked first for 34 consecutive years), with an economic aggregate of 12.91 trillion yuan. The Pearl River Delta region accounts for ~80% of the province's economy. Economic development and a relatively high proportion of construction land are accompanied by a relatively low level of ecosystem services [35]. The main function of the northern Guangdong region is the ecological barrier of the whole province, a large area of forest reserves, so its economy is not fully active, being mainly reflected in high ecosystem services.

The carbon sequestration service in the study was measured based on NPP; therefore, the carbon sequestration level was mainly affected by the surface vegetation coverage. The Nanling Mountain area in northern Guangdong is an important ecological barrier and a core area of ecological security in Guangdong Province and in South China. The forest area in the northern Guangdong mountains accounts for approximately 55% of the entire province woodland area, and the national key ecological area accounts for 85% of the regional land area. Therefore, the carbon sequestration value in northern Guangdong was the highest among the four regions in Guangdong. The carbon sequestration level in Zhaoqing was the highest among the 21 cities because it is close to northern Guangdong and has a good ecological environment and high forest cover, accounting for 70% of the city area. Zhaoqing, Huizhou, and other peripheral areas of the Pearl River Delta are important ecological barriers to the core area of the Pearl River Delta and their ecosystem services are affected by natural and social factors such as urban spatial structure, land cover, and economic development in the process of urbanization in the Pearl River Delta [35]. The carbon sequestration level of Zhanjiang was the lowest among the 21 cities because it mainly consists of cultivated land and its main function is grain production, with a carbon sequestration capacity lower than that of forests. The forest area is small, with an atypical forest structure as more than 80% are commercial forests (including timber forests and economic fruit forests). In addition, as a coastal city, Zhanjiang often suffers from frequent landings of low-pressure tropical storms and typhoons, which have a great impact on forestry production.

Water retention is mainly reflected in forest function. The interception and infiltration of forests can slow down surface water flow intensity, increase the amount of groundwater, control soil desertification, and reduce soil and water loss by restoring vegetation and building water conservation areas [36]. The water retention of forests is manifested in many aspects including water storage, runoff regulation, forest flood reduction, drought resistance, and forest water purification. Through the interception, absorption, and infiltration of precipitation, its spatial and temporal redistribution is conducted to reduce ineffective water use and increase effective water use [37]. High-value areas with high water retention were mainly distributed in areas with high forest coverage. Therefore, northern Guangdong, an important ecological green area in Guangdong Province, had the highest water retention value. Yangjiang City, with the highest water retention, and Zhanjiang City, with the lowest water retention, are both distributed in the west of Guangdong, but their forest coverage rates are vastly different. The forest area in Yangjiang City accounts for approximately 60% of the city area, whereas the forest area in Zhanjiang City only accounts for just over 20% of the city area. Moreover, carbon sequestration and soil retention in Yangjiang City were much higher than in Zhanjiang City (soil retention was 11.5 times higher).

Soil retention is an important ecosystem service that refers to the ability of the ecosystem to regulate erosion to prevent soil loss and retain sediments [23]. Therefore, soil retention is important for preventing regional land degradation and reducing flood risk [38]. Owing to a high forest coverage rate, the soil retention services in Guangdong Province were higher than those in northern China. However, with the significant influence of human activities on rapid urbanization, the soil erosion area in Guangdong Province has been increasing since 2000. By 2019, it had increased to 1.80×10^4 km^2. Light erosion has been observed in 10.09% of the total area of Guangdong Province, accounting for more than 80% of the total erosion area. Cities with high soil retention were in areas with high forest coverage rate, while Zhanjiang City, with the lowest soil retention value, had insufficient forest resources, atypical forest structure, and weak sediment retention ability. Moreover, the coastal area in Zhanjiang City is composed of bare coastal sand, coastal salt-marred soils, and coastal salt soils.

Among the five ecosystem services, food production was the weakest. Because the income of agriculture is significantly lower than that of the secondary and tertiary sectors, the main rural labor force chooses to work in cities to increase family income, and the rural labor force continues to decrease [39]. Although Guangdong Province has abundant photothermal conditions and good soil resources, which together with the poor livelihood guarantee of agricultural land and reduced rental cost of large-scale agricultural land, has led some rural returnee workers to engage in agricultural production mainly planting economic fruit forests and medicinal materials; thus, the use of non-grain agricultural land is promoted. On the other hand, the Pearl River Delta is an area with rapid urbanization and a high economic level. A large amount of cultivated land is occupied by construction land and the food production function of the ecosystem is repeatedly squeezed. According to the *Statistical Yearbook of Guangdong Province*, the grain yield per unit area of Guangdong Province increased from 517.5 t/km^2 to 574.5 t/km^2 from 2009 to 2019 (11.01% growth). However, the total grain production decreased from 131.45×10^5 t to 124.08×10^5 t (5.61% reduction), with the most significant reduction in the mountainous areas of northern Guangdong and the Pearl River Delta. The mountainous areas of northern Guangdong were identified as key national ecological areas according to topographic features and location and some cultivated lands were converted to forest. The Pearl River Delta is mainly used for economic functions. The added value of land in economically developed areas is high, and cultivated land has been occupied by construction land. The food production function in Shenzhen was the lowest because its urbanization rate is 100%, there is almost no distribution of construction land and thus, no agricultural population.

4.2. Analysis of the Mechanisms of Influence of Ecosystem Service Trade-Offs and Synergies

The proportion of trade-offs and synergies between ecosystem services in Guangdong Province was basically the same. The proportion of synergies was slightly higher (55.67%) but almost all were poor synergies; that is, the five kinds of services were at low levels, which is the least ideal state. A total of 21.24% of the province area had "1 medium, 4 low" poor synergies, whereas high synergies accounted for only 0.48% of the provincial area. Most trade-offs were strong, mainly showing low carbon sequestration, high water retention, low biodiversity conservation, medium food production, and low soil retention. The trade-off regions were mainly distributed in Maoming City, Shantou City, Huilai County of Jieyang City, and parts of the Pearl River Delta. In these areas, the forest coverage rate and carbon sequestration were low, and since carbon sequestration, soil retention, and biodiversity conservation were positively correlated, soil retention and biodiversity conservation were also low. These regions are rich in water resources, and water retention services were of high value, so a high trade-off relationship was formed.

In Guangdong Province, the pairwise ecosystem services involving carbon sequestration, water retention, and soil retention showed a significant synergistic relationship because these services are mainly determined by forest cover level. Forest was the land type with the highest level of carbon sequestration. Dense forestland promotes photosynthesis and increases vegetation carbon sequestration capacity. It is also conducive to enhancing water and soil retention. Dense branches, leaves, and large roots in forests can intercept precipitation and surface runoff, which helps maintain soil and prevent erosion. Therefore, these three types of ecosystem services had a higher concentration in forest areas. In bare areas, all three ecosystem services had low values. Also, biodiversity conservation showed poor synergy with carbon sequestration, water retention, and soil retention. The biodiversity function in lush forest areas may be strong and the total number of plant and animal species may be relatively high, but it may not have a strong relationship with nationally protected species of special significance.

The trade-offs and synergies of ecosystem services in Guangdong Province showed clear spatial differences. Paired ecosystem services may show a trade-off relationship in one region and synergistic relationships in other regions. This finding aligns with several previous studies that highlighted heterogeneity within urban ecosystems [6,40,41]. For example, for the carbon sequestration–water retention pair, the coastline of the Pearl River estuary was an LL synergy area; however, the partial region of northern Guangdong and Western Guangdong were HL or LH trade-off areas. The relationships between the same ecosystem services may show completely different characteristics in different regions because of the combined influence of different natural environments and socioeconomic characteristics [42,43]. The geomorphological conditions of Guangdong Province are complex as the region is known as "seven mountains, one water, and two fields." It gradually declines from the northern mountains to the southern coastal areas, forming a geomorphic pattern dominated by the northern middle mountains, central low mountains and hills, and southern plains. Under different geomorphic conditions, the regional ecosystem service capacities and the trade-offs and synergies between the paired services also had significant differences. Guangdong Province is a province of China with a large economy, and its economic center is mainly distributed in the Pearl River Delta region. Human interference is strong in this region, exhibited by intense land development and the destruction of various ecological environments due to industrial development. The same is happening in other parts of the world with rapid urbanization [40,41]. This decline in ecosystem service capacity and destruction of natural vegetation inhibit the positive succession of ecosystems, reducing their regulatory service capacity. In contrast, northern Guangdong is an ecologically protected area, and its overall ecological environment is better.

Guangdong Province is rich in natural resources and has a high level of ecosystem services. However, poor synergies and strong trade-offs remain dominant among the ecosystem services. Sufficient attention should be paid to the protection of ecosystem services, and efforts should be made to practice ecological urban construction while steadily improving social and economic levels. Guangdong Province also represents an economically developed region in developing countries. In future planning, optimized allocation of land can be effectively conducted based on the analysis results of the trade-off and synergy relationship between regional ecosystem services. Adjusting the quantity and spatial structure of land use types with different ecosystem services can facilitate promotion of the synergistic relationship of ecosystem services actively and adjust the trade-off relationship, such that the harmonious coexistence between humans and nature is achieved.

4.3. Uncertainty

Ecosystem services are the goods and services provided by ecosystems to society [23,44], and include dozens of services of four kinds: providing products, regulating functions, supporting functions, and cultural services. Currently, no model can comprehensively evaluate all ecosystem services and different methods of evaluating the same ecosystem services in the same region produce different results. In this study, ecosystem services were selected for analysis according to the characteristics of the research object and the research region [45]. This study used "a spatial dataset of ecosystem services in China", which included six important ecosystem services, namely food production, soil retention, water retention, windbreak and sand fixation, biodiversity conservation, and carbon sequestration. The tropical and subtropical monsoon climate in the study area was significant, with abundant rainfall and abundant water resources; thus, windbreak and sand fixation were not considered in the study.

In addition, it is necessary to note that these five ecosystem services were divided into three levels using a natural breakpoint method (Table 2). Therefore, since the level of ecosystem services was relative to that of the local region, it is possible that the low-value ranges in some ecosystem services were still higher than those in some ecologically fragile areas in northwest China.

5. Conclusions

(1) The ecosystem services in Guangdong Province showed clear spatial heterogeneity. Owing to a humid climate and high forest coverage, the area showed strong water retention. Northern Guangdong had high water retention and carbon sequestration, and the highest soil retention in the province. Food production services were mainly concentrated in Western Guangdong.

(2) Overall, in Guangdong Province, three pairs of ecosystem services, water retention–soil retention, carbon sequestration–water retention, carbon sequestration–soil retention, showed strong positive correlations and strong synergistic relationships. There were strong negative correlations between food production–water retention, food production–soil retention, and food production–biodiversity conservation. There was a strong trade-off between food production and water retention.

(3) The trade-offs and synergies between the ecosystem service pairs were spatially different. In northern Guangdong, forests are widely distributed; the area is a national nature reserve with a good ecological environment. It is also an area where HH synergies are mainly observed between carbon sequestration and water retention, carbon sequestration and biodiversity maintenance, water retention and biodiversity conservation, and soil retention and biodiversity conservation. The relationships between carbon sequestration and food production, water retention and food production, and soil retention and biodiversity conservation are similar and mainly show trade-off relationships; HL tradeoffs are concentrated in northern Guangdong.

Author Contributions: Q.X. was mainly responsible for writing the full text; Y.Y. was mainly responsible for the structure of the paper; R.Y. was mainly responsible for the mechanisms of influence of ecosystem service trade-offs and synergies; L.-S.Z. was mainly responsible for the spatial differentiation of ecosystem services. Z.-Q.L. and S.-H.S. were mainly responsible for data processing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (No. 42101242, 41907001); the Natural Science Foundation of Guangdong Province (No. 2023A1515012373); the Philosophy and Social Sciences Planning Program of Guangdong Province (GD20YGL07); and the Science and Technology Planning Program of Guangzhou, China (No. 202102080254, 202102021168).

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare that there are no conflicts of interest.

References

1. Daily, G.C. *Nature's Services: Societal Dependence on Natural Ecosystems*; Island Press: Washington, DC, USA, 1997; pp. 454–464. [CrossRef]
2. Niu, L.; Shao, Q.; Ning, J.; Huang, H. Ecological changes and the tradeoff and synergy of ecosystem services in western China. *J. Geogr. Sci.* **2022**, *32*, 1059–1075. [CrossRef]
3. European Environment Agency. Imperviousness and Imperviousness Change in Europe. 2021. Available online: https://www.eea.europa.eu/data-and-maps/indicators/imperviousness-change-2 (accessed on 24 March 2023).
4. Belaire, J.A.; Higgins, C.; Zoll, D.; Lieberknecht, K.; Bixler, R.P.; Neff, J.L.; Keitt, T.H.; Jha, S. Fine-scale monitoring and mapping of biodiversity and ecosystem services reveals multiple synergies and few tradeoffs in urban green space management. *Sci. Total Environ.* **2022**, *849*, 157801. [CrossRef] [PubMed]
5. Wang, X.; Peng, J.; Luo, Y.; Qiu, S.; Dong, J.; Zhang, Z.; Vercruysse, K.; Grabowski, R.C.; Meersmans, J. Exploring social-ecological impacts on trade-offs and synergies among ecosystem services. *Ecol. Econ.* **2022**, *197*, 107438. [CrossRef]
6. Cord, A.; Bartkowski, B.; Beckmann, M.; Dittrich, A.; Hermans-Neumann, K.; Kaim, A.; Lienhoop, N.; Locher-Krause, K.; Priess, J.; Schröter-Schlaack, C.; et al. Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. *Ecosyst. Serv.* **2017**, *28*, 264–272. [CrossRef]
7. Li, T.; Lü, Y.; Fu, B.; Hu, W.; Comber, A.J. Bundling ecosystem services for detecting their interactions driven by large-scale vegetation restoration: Enhanced services while depressed synergies. *Ecol. Indic.* **2019**, *99*, 332–342. [CrossRef]

8. Baiqiu, W.; Junbang, W.; Shuhua, Q.; Shaoqiang, W.; Yingnian, L. Review of methods to quantify trade-offs among ecosystem services and future model developments. *J. Resour. Ecol.* **2019**, *10*, 225–233. [CrossRef]
9. Shen, J.; Li, S.; Liang, Z.; Liu, L.; Li, D.; Wu, S. Exploring the heterogeneity and nonlinearity of trade-offs and synergies among ecosystem services bundles in the Beijing-Tianjin-Hebei urban agglomeration. *Ecosyst. Serv.* **2020**, *43*, 101103. [CrossRef]
10. Yang, S.; Zhao, W.; Liu, Y.; Wang, S.; Wang, J.; Zhai, R. Influence of land use change on the ecosystem service trade-offs in the ecological restoration area: Dynamics and scenarios in the Yanhe watershed, China. *Sci. Total Environ.* **2018**, *644*, 556–566. [CrossRef]
11. Hu, Y.; Peng, J.; Liu, Y.; Tian, L. Integrating ecosystem services trade-offs with paddy land-to-dry land decisions: A scenario approach in Erhai Lake Basin, southwest China. *Sci. Total Environ.* **2018**, *625*, 849–860. [CrossRef]
12. Zhang, Z.; Liu, Y.; Wang, Y.; Liu, Y.; Zhang, Y.; Zhang, Y. What factors affect the synergy and tradeoff between ecosystem services, and how, from a geospatial perspective? *J. Clean. Prod.* **2020**, *257*, 120454. [CrossRef]
13. Peng, J.; Hu, X.; Zhao, M.; Liu, Y.; Tian, L. Research progress on ecosystem service trade-offs: From cognition to decision-making. *Acta Geogr. Sin.* **2017**, *72*, 960–973. [CrossRef]
14. Allen, W.J.; Bufford, J.L.; Barnes, A.D.; Barratt, B.I.; Deslippe, J.R.; Dickie, I.A.; Goldson, S.L.; Howlett, B.G.; Hulme, P.E.; Lavorel, S.; et al. A network perspective for sustainable agroecosystems. *Trends Plant Sci.* **2022**, *27*, 769–780. [CrossRef] [PubMed]
15. Damania, R.; Russ, J.; Wheeler, D.; Barra, A.F. The road to growth: Measuring the tradeoffs between economic growth and ecological destruction. *World Dev.* **2018**, *101*, 351–376. [CrossRef]
16. Kluger, L.C.; Gorris, P.; Kochalski, S.; Mueller, M.S.; Romagnoni, G. Studying human–nature relationships through a network lens: A systematic review. *People Nat.* **2020**, *2*, 1100–1116. [CrossRef]
17. Seddon, N.; Chausson, A.; Berry, P.; Girardin, C.A.J.; Smith, A.; Turner, B. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philos. Trans. R. Soc. B Biol. Sci.* **2020**, *375*, 20190120. [CrossRef] [PubMed]
18. Vanham, D.; Leip, A.; Galli, A.; Kastner, T.; Bruckner, M.; Uwizeye, A.; van Dijk, K.; Ercin, E.; Dalin, C.; Brandão, M.; et al. Environmental footprint family to address local to planetary sustainability and deliver on the SDGs. *Sci. Total Environ.* **2019**, *693*, 133642. [CrossRef]
19. Moore, M.R.; Doubek, J.P.; Xu, H.; Cardinale, B.J. Hedonic price estimates of lake water quality: Valued attribute, instrumental variables, and ecological-economic benefits. *Ecol. Econ.* **2020**, *176*, 106692. [CrossRef]
20. Chanchitpricha, C.; Fischer, T.B. The role of impact assessment in the development of urban green infrastructure: A review of EIA and SEA practices in Thailand. *Impact Assess. Proj. Apprais.* **2022**, *40*, 191–201. [CrossRef]
21. Tian, L.; Li, Y.; Yan, Y.; Wang, B. Measuring urban sprawl and exploring the role planning plays: A shanghai case study. *Land Use Policy* **2017**, *67*, 426–435. [CrossRef]
22. Marando, F.; Heris, M.P.; Zulian, G.; Udías, A.; Mentaschi, L.; Chrysoulakis, N.; Maes, J. Urban heat island mitigation by green infrastructure in European Functional Urban Areas. *Sustain. Cities Soc.* **2022**, *77*, 103564. [CrossRef]
23. Costanza, R.; d'Arge, R.; de Groot, R.; Farber, S.; Grasso, M.; Hannon, B.; Limburg, K.; Naeem, S.; O'Neill, R.V.; Paruelo, J.; et al. The value of the world's ecosystem services and natural capital. *Nature* **1997**, *387*, 253–260. [CrossRef]
24. Millennium Ecosystem Assessment (MEA). *Ecosystems and Human Well-Being*; Island Press: Washington, DC, USA, 2005.
25. Schwarz, N.; Bauer, A.; Haase, D. Assessing climate impacts of planning policies—An estimation for the urban region of Leipzig (Germany). *Environ. Impact Assess. Rev.* **2011**, *31*, 97–111. [CrossRef]
26. Carreño, L.; Frank, F.; Viglizzo, E. Tradeoffs between economic and ecosystem services in Argentina during 50 years of land-use change. *Agric. Ecosyst. Environ.* **2012**, *154*, 68–77. [CrossRef]
27. Jia, X.; Fu, B.; Feng, X.; Hou, G.; Liu, Y.; Wang, X. The tradeoff and synergy between ecosystem services in the Grain-for-Green areas in Northern Shaanxi, China. *Ecol. Indic.* **2014**, *43*, 103–113. [CrossRef]
28. Niu, T.; Yu, J.; Yue, D.; Yang, L.; Mao, X.; Hu, Y.; Long, Q. The temporal and spatial evolution of ecosystem service synergy/trade-offs based on ecological units. *Forests* **2021**, *12*, 992. [CrossRef]
29. Vallet, A.; Locatelli, B.; Levrel, H.; Wunder, S.; Seppelt, R.; Scholes, R.J.; Oszwald, J. Relationships between ecosystem services: Comparing methods for assessing tradeoffs and synergies. *Ecol. Econ.* **2018**, *150*, 96–106. [CrossRef]
30. Costanza, R.; De Groot, R.; Braat, L.; Kubiszewski, I.; Fioramonti, L.; Sutton, P.; Farber, S.; Grasso, M. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosyst. Serv.* **2017**, *28*, 1–16. [CrossRef]
31. Huang, F.; Zuo, L.; Gao, J.; Jiang, Y.; Du, F.; Zhang, Y. Exploring the driving factors of trade-offs and synergies among ecological functional zones based on ecosystem service bundles. *Ecol. Indic.* **2023**, *146*, 109827. [CrossRef]
32. Ouyang, Z.; Zhang, L.; Wu, B.; Li, X.; Xu, W.; Xiao, Y.; Zheng, H. An ecosystem classification system based on remote sensor information in China. *Acta Ecol. Sin.* **2015**, *35*, 219–226. [CrossRef]
33. Zhang, L.; Xiao, Y.; Zheng, H.; Xu, W.H.; Lu, F.; Jiang, L.; Rao, E.M.; Xiao, Y.; Wu, B.F.; Zeng, Y.; et al. A spatial dataset of ecosystem services in China (2010). *Chin. Sci. Data* **2018**, *3*, 2018-09-06. [CrossRef]
34. Zhang, J.J.; Zhu, W.B.; Zhu, L.Q.; Li, Y.H. Multi-scale analysis of trade-off/synergy effects of forest ecosystem services in the Funiu Mountain Region. *Acta Geogr. Sin.* **2020**, *75*, 975–988. [CrossRef]
35. Xu, Q.; Yang, R.; Zhuang, D.; Lu, Z. Spatial gradient differences of ecosystem services supply and demand in the Pearl River Delta region. *J. Clean. Prod.* **2020**, *279*, 123849. [CrossRef]
36. Shah, N.W.; Baillie, B.R.; Bishop, K.; Ferraz, S.; Högbom, L.; Nettles, J. The effects of forest management on water quality. *For. Ecol. Manag.* **2022**, *522*, 120397. [CrossRef]

37. Prescott, C.E.; Grayston, S.J. TAMM review: Continuous root forestry—Living roots sustain the belowground ecosystem and soil carbon in managed forests. *For. Ecol. Manag.* **2023**, *532*, 120848. [CrossRef]
38. Liu, Y.; Zhao, W.; Jia, L. Soil conservation service: Concept, assessment, and outlook. *Acta Ecol. Sin.* **2019**, *39*, 432–440. [CrossRef]
39. Yang, R.; Luo, X.; Xu, Q.; Zhang, X.; Wu, J. Measuring the impact of the multiple cropping index of cultivated land during continuous and rapid rise of urbanization in China: A study from 2000 to 2015. *Land* **2021**, *10*, 491. [CrossRef]
40. Jafarzadeh, A.A.; Mahdavi, A.; Shamsi, S.R.F.; Yousefpour, R. Assessing synergies and trade-offs between ecosystem services in forest landscape management. *Land Use Policy* **2021**, *111*, 105741. [CrossRef]
41. Cueva, J.; Yakouchenkova, I.A.; Fröhlich, K.; Dermann, A.F.; Dermann, F.; Köhler, M.; Grossmann, J.; Meier, W.; Bauhus, J.; Schröder, D.; et al. Synergies and trade-offs in ecosystem services from urban and peri-urban forests and their implication to sustainable city design and planning. *Sustain. Cities Soc.* **2022**, *82*, 103903. [CrossRef]
42. Li, G.; Jiang, C.; Gao, Y.; Du, J. Natural driving mechanism and trade-off and synergy analysis of the spatiotemporal dynamics of multiple typical ecosystem services in Northeast Qinghai-Tibet Plateau. *J. Clean. Prod.* **2022**, *374*, 134075. [CrossRef]
43. Huang, J.; Zheng, F.; Dong, X.; Wang, X.-C. Exploring the complex trade-offs and synergies among ecosystem services in the Tibet autonomous region. *J. Clean. Prod.* **2023**, *384*, 135483. [CrossRef]
44. Divinsky, I.; Becker, N.; Bar, P. Ecosystem service tradeoff between grazing intensity and other services—A case study in Karei-Deshe experimental cattle range in northern Israel. *Ecosyst. Serv.* **2017**, *24*, 16–27. [CrossRef]
45. Xu, Q.; Dong, Y.-X.; Yang, R. Influence of land urbanization on carbon sequestration of urban vegetation: A temporal cooperativity analysis in Guangzhou as an example. *Sci. Total Environ.* **2018**, *635*, 26–34. [CrossRef] [PubMed]

land

Article

Evolution Model, Mechanism, and Performance of Urban Park Green Areas in the Grand Canal of China

Zihan Cai [1,*], Sidong Zhao [2], Mengshi Huang [1] and Congguo Zhang [3,*]

[1] School of Architecture & Art Design, Hebei University of Technology, Tianjin 300401, China; 2019098@hebut.edu.cn
[2] School of Architecture, Southeast University, Nanjing 210096, China; 230189013@seu.edu.cn
[3] Spatial Planning Center, Yangtze Delta Region Institute of Tsinghua University, Zhejiang, Jiaxing 314006, China
* Correspondence: 2020108@hebut.edu.cn (Z.C.); zcg96@163.com (C.Z.)

Abstract: Urban park green areas are part of territorial space planning, shouldering the mission of providing residents with high-quality ecological products and public space. Using a combination of several measurement models such as the BCG (Boston Consulting Group) matrix, ESDA (Exploratory Spatial Data Analysis), MLR (Machine Learning Regression), GWR (Geographically Weighted Regression), and GeoDetector, this paper presents an empirical study on the changes in Urban Park Green Areas (UPGAs) in the Grand Canal of China. By quantitatively measuring the spatio–temporal evolution patterns of UPGAs, this study reveals the driving mechanisms behind them and proposes policy recommendations for planning and management based on performance evaluation. The spatio–temporal evolution of UPGAs and their performance in China's Grand Canal are characterized by significant spatial heterogeneity and correlation, with diversified development patterns such as HH (High-scale–High-growth), HL (High-scale–Low-growth), LH (Low-scale–High-growth), and LL (Low-scale–Low-growth) emerging. The evolution performance is dominated by positive oversupply and positive equilibrium, where undersupply coexists with oversupply. Therefore, this paper recommends the implementation of a zoning strategy in the future spatial planning of ecological green areas, urban parks, and green infrastructure. It is also recommended to design differentiated construction strategies and management policies for each zoning area, while promoting inter-city mutual cooperation in the joint preparation and implementation of integrated symbiosis planning. Furthermore, the spatio–temporal evolution of the UPGAs in the Grand Canal of China is influenced by many factors with very complex dynamic mechanisms, and there are significant differences in the nature, intensity, spatial effects, and interaction effects between different factors. Therefore, in the future management of ecological green areas, urban parks, and green infrastructure, it is necessary to interconnect policies to enhance their synergies in population, aging, industry and economy, and ecological civilization to maximize the policy performance.

Keywords: urban park; evolution mode; driving mechanism; spatial planning; grand canal; China

Citation: Cai, Z.; Zhao, S.; Huang, M.; Zhang, C. Evolution Model, Mechanism, and Performance of Urban Park Green Areas in the Grand Canal of China. *Land* **2024**, *13*, 42. https://doi.org/10.3390/land13010042

Academic Editors: Luca Battisti, Fabrizio Aimar and Federico Cuomo

Received: 13 November 2023
Revised: 26 December 2023
Accepted: 27 December 2023
Published: 30 December 2023

1. Introduction

1.1. Background

In the national spatial planning system, the planning for urban green areas is one of the most important projects, aimed at providing high-quality ecosystem services and public spaces for residents in China. Scientific planning of the quantity, quality, and spatial structure of the supply of urban green areas, especially Urban Park Green Areas (UPGAs), will significantly foster a more sustainable and livable urban environment [1,2]. In addition, as the construction of the Yangtze River Economic Belt, the protection and utilization of the Grand Canal and the construction of its cultural belt, and the ecological protection and high-quality development of the Yellow River Basin have been successively upgraded to national strategies, watershed spatial governance has become a key task of territorial spatial planning and a hotspot in academic research [3]. Therefore, quantitatively analyzing the spatio–temporal evolution patterns and driving mechanisms of UPGAs from a regional holistic perspective and evaluating the performance of land supply and demand will provide a basis for green infrastructure planning practice in watersheds and will help establish a technological system adapted to territorial spatial planning in these areas.

1.2. Literature Review

1.2.1. Urban Green Areas and Parkland

Current research on urban green areas mainly deals with planning methods and management policies [4,5], accessibility and satisfaction assessment [6,7], spatio–temporal dynamics and their influencing factors [8,9], value for ecosystem services and health [10,11], and other areas [12], while research on urban parkland focuses on areas such as spatial siting and configuration [13,14], needs assessment [15], planning methods [16], and willingness to pay [17]. Overall, there has been a large body of research on urban green areas and parkland, but still less attention has been paid to UPGAs [18]. For example, given that the unbalanced distribution of UPGAs has a significant impact on the well-being of residents, Li [19] and Xu [20] proposed an optimal spatial division plan for the service levels of UPGAs from the perspective of opportunity equity and spatial scale, based on the case studies of Taiyuan and Xuchang. Doll [21] assessed the greenness of UPGAs in Australia from the perspective of landscape preference and water consumption. Wang [22] quantitatively measured the equity of UPGAs in the central city of Beijing, analyzing the space to reveal a serious mismatch between the supply and demand of green areas. Yin [23] quantitatively examined the retention capacity of 176 urban park green areas within the Fifth Ring Road of Beijing for PM2.5 and endeavored to provide a basis for the design and construction of UPGAs to improve air quality. Biernacka [24] mapped and analyzed the dynamics of UPGAs in Poland, and they suggested the inclusion of informal green areas in urban planning. Engstrom [25] analyzed the advantages and disadvantages of using a hedonic price approach to capture the values of UPGAs in urban planning, and Ayele [26] studied the management model of UPGAs in Addis Ababa during rapid urbanization in Ethiopia.

1.2.2. Basin Planning and the Grand Canal

As Molle [27] and Antwi [28] put it, watershed planning has its origins in regional water resource management, but the embeddedness of other natural and ecological resource management systems has contributed to its gradual transformation into a new concept of socio–political life and spatial governance systems. Suhardiman [29] argued that watershed planning has evolved in Nepal as an arena for power operations and struggles, with its cross administrative boundaries jointly created by different government agencies. Essentially, watershed planning is a debate between multiple interests on development opportunities around the two perspectives of conservation and utilization, during which a large number of integrated modeling methods [30,31] and planning tools are created [32]. At present, the study of artificially excavated canals plays an important role in watershed planning, especially in China, the United States, Egypt, and India [33]. For the Grand Canal of China, the current research mainly focuses on the fields of cultural heritage, heritage and ecological protection, tourism development, land use, urban and rural spatial changes, and human habitat analysis. It has moved beyond the construction of water facilities and the development of cultural belts to green belts and economic belts [34] (Table 1).

Table 1. Literature review of the Grand Canal of China.

Areas	Viewpoints
Cultural Heritage and Ecological Protection	I. Study the distribution, characteristics, and influencing factors of historical relics and intangible cultural heritage along the canal [35,36] and further propose strategies for protection and utilization [37]. II. Assess the value of cultural heritage and relics along the canal and determine the adaptive landscape development methods [38–40]. III. Emphasize the evaluation of canal habitat quality [41], ecological functions [42], and pollution risks [43] and analyze their impact on ecosystem services [44].
Tourism development	I. Value the construction of tourism destinations and the construction of the tourism industry system, including the image perception of tourism destinations and its impact on tourism loyalty [45,46], tourism value assessment and resource utilization [47,48], tourism spatial development models [49], and regional tourism openness and cooperation [50]. II. Analyze the coupling relationship between tourism and ecology, heritage, and climate, including the impact of climate change on the development of canal tourism [51], the collaboration between tourism and ecosystems and their development obstacles [52], and the correlation between the spatio–temporal distribution of cultural heritage and tourism response [53].
Land use and Urban-rural changes	I. Analyze the level of sustainable and healthy land use along the canal [54] and land use/cover changes [55] and their impact on regional development [56]. II. Analyze the rise and fall of cities along the canal and spatial pattern and structural changes and their influencing factors, especially the role of canal logistics and flooding [57,58]. III. Analyze the geographical evolution of rural spatial settlements along the canal and its influencing factors, especially traditional villages and historical and cultural ancient villages [59–61].
Sustainable Development	I. Assess the spatial sustainable development of the canal basin [62] and its contribution to regional development [63]. II. Analyze the spatio–temporal characteristics of urbanization and the socio–economic benefits of canal land using the coupled coordination degree model to identify the synergistic development model of water–economy–innovation [64].

1.2.3. Research Gaps and Questions

There are three shortcomings in the current research. First, there is a wealth of research on urban green areas separated from parkland, but fewer studies combining the two, and such studies mainly focus on single-city case studies, lacking an analysis of the whole area and not matching the needs of watershed planning. Second, studies on the Grand Canal are mainly concerned with culture, ecological protection, and tourism development. Few scholars have focused on land use and change, except for Xia [65], who analyzed the impact of green areas on the well-being of residents in the Hangzhou section of the Grand Canal. Third, the Grand Canal is essentially a regional cultural, economic, and green belt, but current research lacks spatial correlation analysis from a regional perspective, and discussion of the driving mechanism ignores the influence of spatial and interactive effects.

To address the aforementioned shortcomings, this paper introduces a combination of spatial measurement models to study the whole area of the Grand Canal and analyze the spatio–temporal evolution patterns of UPGAs to reveal the driving mechanisms behind them, and it proposes suggestions and strategies for green areas or green infrastructure planning based on the change performance evaluation. This study aims to (1) quantitatively measure the evolutionary patterns of the UPGAs in the Grand Canal and reveal their spatial effects through the BCG (Boston Consulting Group) matrix and ESDA (Exploratory Spatial Data Analysis) in both temporal and spatial dimensions; (2) quantitatively measure the direct influence of different influencing factors on their spatio–temporal evolution patterns, as well as the spatial and interactive effects of the influencing factors using the MLR (Machine Learning Regression) method, the GWR (Geographically Weighted Regression) method, and GeoDetector; (3) evaluate the performance of their changes according to the indicators defined in the United Nations Sustainable Development Agenda, which dynamically analyzed the match between land supply and population demand; and (4) provide suggestions for their management policy and planning design based on the analysis results.

2. Materials and Methods

2.1. Study Area

The Grand Canal of China, with a history of more than 1000 years and spanning thousands of kilometers from north to south, crosses a number of water systems from north to south, such as the Haihe River, the Yellow River, the Huaihe River, the Yangtze River, Taihu Lake, and the Qiantang River, and has served as an important water transportation channel as well as an artery for the economic and cultural exchanges between the north and south of China since ancient times. The Grand Canal of China, consisting of the Beijing–Hangzhou Grand Canal, the Sui–Tangshan Grand Canal, and the Zhedong Canal, was officially approved by UNESCO on 22 June 2014 for inclusion in the World Heritage List. The State Council issued the Outline of the Plan for the Protection, Inheritance, and Utilization of the Grand Canal Culture in February 2019, which defines the spatial scope of the Grand Canal basin as the two municipalities of Beijing and Tianjin and the six provinces of Hebei, Shandong, Jiangsu, Zhejiang, Henan, and Anhui, comprising a total of 86 cities. The study area in this paper is the same as the planned scope, covering all 86 cities (Figure 1).

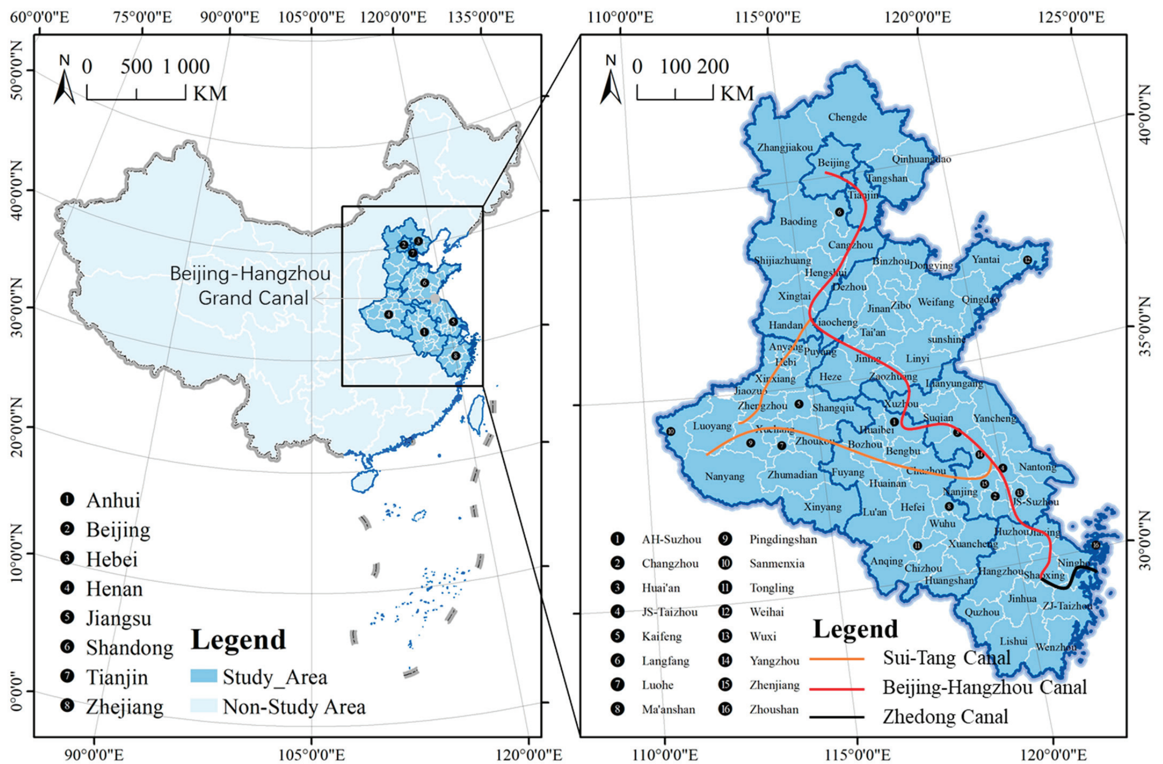

Figure 1. The Grand Canal and its location in China.

2.2. Research Steps and Technical Route

This study is based on a variety of measurement models, and it is performed in four steps (Figure 2):

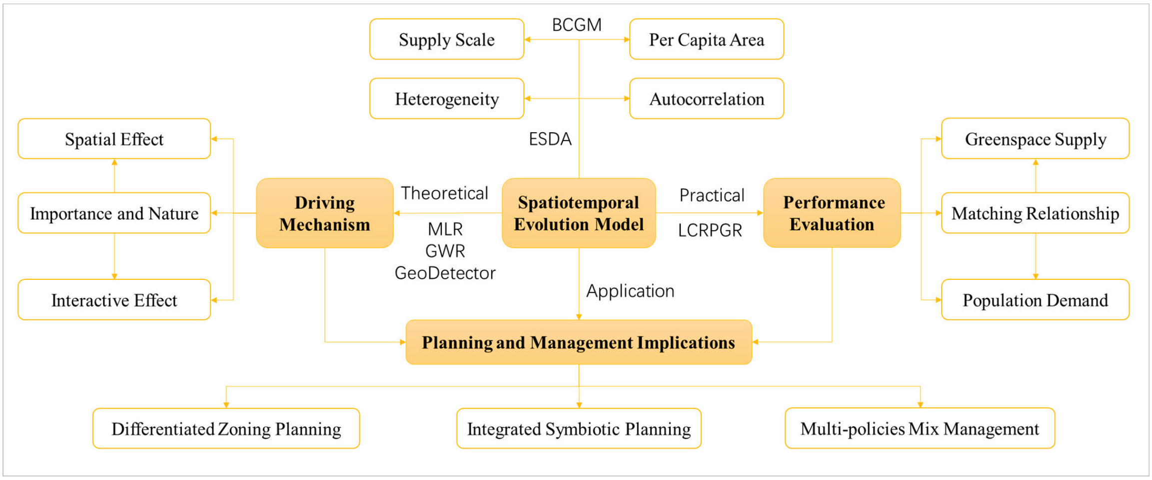

Figure 2. Technical route for the study of urban park green areas within the Grand Canal.

The first step is to analyze the spatio–temporal evolution patterns of the supply scale and per-capita area of UPGAs in the Grand Canal using the BCG (Boston Consulting Group) matrix, and to analyze their spatial heterogeneity and autocorrelation through ESDA (Exploratory Spatial Data Analysis).

The second step is to quantitatively analyze the driving mechanisms of changes in the scale of their supply and per-capita area, including the importance of factors, spatial effects, and interaction effects, based on a combination of MLR (Machine Learning Regression), GWR (Geographically Weighted Regression), and GeoDetector.

The third step is to analyze the match between their supply and demand from the perspective of sustainable development based on the LCRPGR (Ratio of Land Consumption Rate to Population Growth Rate).

The fourth step is to propose planning and management suggestions as guidance and a basis for green area planning and green infrastructure policy design based on the analysis results of the first three steps.

2.3. Research Methods and Indicator Selection

2.3.1. Boston Consulting Group (BCG) Matrix

The BCG matrix is often used in enterprise strategy management to classify the development status of businesses or products into four types, Star, Question, Cow, and Dog, and propose differentiated development strategies based on the combined analysis of the relative market share and growth rate of business departments or products. A development strategy is needed for Star products, and further investment is required to support their rapid expansion in the market and to make them the leading products of the enterprise. Cow products require a profit strategy, but the core of future development strategies is not to increase business investment, enterprise output, or market supply, but rsther to quickly recover funds through high product profits to support the development of Star products. For Question products, more research is needed and flexible strategies should be developed according to the actuality. Specifically, it is necessary to, based on the survey and research results, select some potential subcategories for key investments, while abandoning others. Dog products should be stopped, either by abandonment or recycling, in order to decisively stop loss, as they are the products that have been in a period of decline, unable to create more earnings for the enterprise.

In this paper, a concept is introduced to analyze the spatio–temporal evolutionary patterns of UPGAs in the Grand Canal of China, where Relative Share (*RS*) and Growth Rate (*GR*) represent the regional status in the spatial dimension and the growth capacity in the temporal dimension, respectively. With their median as the threshold, the spatio–temporal evolutionary patterns of UPGAs of the 86 cities in the study area can be categorized into four quadrants—HH (High-scale–High-growth), HL (High-scale–Low-growth), LH (Low-scale–High-growth), LL (Low-scale–Low-growth)—by the Cartesian coordinate system. With UPG_i and UPG'_i as the indicators for UPGAs in the i-th city in 2020 and 2010, respectively, and UPG_{max} as the maximum value for 86 cities in the study area, RS and GR are calculated as follows [66]:

$$RS = \frac{UPG_i}{UPG_{max}} \times 100\% \tag{1}$$

$$GR = \left(\frac{UPG_i - UPG'_i}{UPG'_i} - 1 \right) \times 100\% \tag{2}$$

2.3.2. Exploratory Spatial Data Analysis (ESDA)

This paper employs ESDA to quantitatively judge and visualize the spatial features of UPGAs, including spatial autocorrelation and spatial heterogeneity. Moran's I index is used to measure the overall strength of spatial autocorrelation, and a value greater or less than zero represents the positive or negative spatial autocorrelation in the spatial distribution of UPGAs, respectively, otherwise it represents a random distribution [67,68]. To further measure the localized characteristics of spatial associations, the Getis–Ord G_i^* index is introduced to classify the cities in the study area into four types: hot, sub-hot, sub-cold, and cold. To measure regional differences in UPGAs, coefficient of variation and spatial clustering methods are introduced to represent and visually demonstrate spatial heterogeneity. A larger coefficient of variation indicates a greater regional difference in UPGAs, with 0.36 and 0.16 being the thresholds to determine high and low levels of spatial heterogeneity [69]. With $\overline{UPG}$ being the mean of UPGA metrics, S being their standard deviation, and W_{ij} being the spatial weight, Moran's I, Getis–Ord G_i^*, and CV are calculated as follows [70]:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(UPG_i - \overline{UPG}\right)\left(UPG_j - \overline{UPG}\right)}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\right)\sum_{i=1}^{n}\left(UPG_i - \overline{UPG}\right)^2} \tag{3}$$

$$G_i^* = \frac{\sum_{j=1}^{n} W_{ij} UPG_i - \overline{UPG}\sum_{j=1}^{n} W_{ij}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} W_{ij}^2 - \left(\sum_{j=1}^{n} W_{ij}\right)^2\right]}{n-1}}} \tag{4}$$

$$CV = S/\overline{UPG}, \quad S = \sqrt{\frac{\sum_{i=1}^{n}\left(UPG_i - \frac{\sum_{i=1}^{n} UPG_i}{n}\right)^2}{n}}, \quad \overline{UPG}\frac{\sum_{i=1}^{n} UPG_i}{n} \tag{5}$$

2.3.3. Machine Learning Regression (MLR)

Given the nonlinear characteristics of distribution planning for UPGAs and machine learning regression methods that do not rely on a priori subjective human experience, a non-linear econometric model is adopted to analyze the importance of influencing factors [71]. In this paper, the decision tree, random forest, adaboost, and ExtraTrees algorithms in machine learning regression models are used to analyze the influence of different factors on the spatio–temporal evolution patterns of UPGAs. Decision tree, a tree-like structure, tests the data sample from the root node, divides the data sample into different data sample subsets according to different results, and calculates the data through a series of rules [72]. Random forest is a supervised machine learning algorithm constructed by integrating decision tree-based learners, which introduces randomness into the training process of decision tree to make it excellent in overfitting and noise resistance [73]. The AdaBoost model is an iterative algorithm that adds a new weak classifier in each round until a predetermined sufficiently small error rate is reached [74]. Extra-trees are derived from the traditional decision tree algorithm, characterized by the direct use of random features and thresholds in the node division of the decision tree, resulting in a larger and more random shape and difference in each decision tree [75]. The purpose of introducing machine learning regression in this paper is to measure the importance of factors, not to make predictions. Therefore, all data are included in the calculation, and the final result is determined according to goodness of fit and the comparative analysis of different algorithms.

Dependent variables include the supply scale of UPGAs and per-capita area of UPGAs, labeled with Y_1 and Y_2, respectively. For independent variables, the combined influence of social, economic, and natural factors should be considered (Table 2). For social factors, population density represents the overall impact of a population aged 60 and above, and the proportion of population aged 60 and above represents the impact of special aging groups [76]. Outflow population indicates the impact of a semi-urbanized, transient population [77]. Of the economic factors, GDP represents the impact of the size of the economy [78]. Per-capita GDP represents the impact of the stage and quality of economic development [79,80] and fiscal self-sufficiency rate represents the government's ability to intervene in the economy [81,82]. In terms of natural factors, topography represents the impact of topographic complexity [83], average temperature represents the impact of climate change, especially the urban heat island effect [84], and ventilation coefficient represents the impact of regional wind environment and urban air quality [85,86]. According to the measurement of covariance between factors using the least squares linear regression model, the maximum value of VIF for per-capita GDP among the nine independent variables reaches 8.25, but is still less than 10, indicating that the covariance of the independent variables is weak and can be almost ignored. The dependent variable data came from the China Urban Construction Statistical Yearbook; the population data came from the population census; the economic data came from the China City Statistical Yearbook and the statistical yearbooks of eight provinces/municipalities directly under the central government; the topographic relief data come from the Relief Degree of Land Surface Dataset of China (1 km) [87,88]; the average temperature data came from data.cma.cn; and ventilation coefficients were calculated from ECMWF re-analysis-interim data by the methods of Broner [89], Hering [90], and Chen [91]. Equations (6) and (7) are used for the positive and negative indicators in the standardization of dependent and independent variables, where $D_i^{+/-}$ is a standardized value, D_i is the original value, and D_{Max} and D_{Min} are the maximum and minimum values of the original data, respectively.

$$D_i^+ = \frac{D_i - D_{Min}}{D_{Max} - D_{Min}} + 0.001 \quad (6)$$

$$D_i^- = \frac{D_{Max} - D_i}{D_{Max} - D_{Min}} + 0.001 \quad (7)$$

Table 2. Indicator selection of independent variables.

Indicator		Code	VIF
Supply scale of UPGAs		Y_1	--
Per-capita area of UPGAs		Y_2	--
Society	Population density	X_1	1.14
	Proportion of population aged 60 and above	X_2	1.93
	Outflow population	X_3	3.49
Economic	GDP	X_4	2.84
	Per-capita GDP	X_5	8.25
	Fiscal self-sufficiency rate	X_6	5.41
Natural	Topography	X_7	1.27
	Average temperature	X_8	1.58
	Ventilation coefficient	X_9	1.63

2.3.4. Geographically Weighted Regression (GWR)

In this study, GWR is used to analyze the impact of each factor on the spatio–temporal evolution patterns of UPGAs. GWR improves the computational accuracy of the regression model by creating localized regression equations for each city and incorporating the spatial autocorrelation and heterogeneity of UPGA changes into the regression process [92]. With Y_i representing the spatio–temporal evolution pattern of UPGAs of the *i*-th city (HH, HL, LH, LL are assigned values of 4, 3, 2, and 1, respectively, in the calculation), X_{ik} being the *k*-th independent variable (influencing factor), β_0 being a constant term, (μ_i, v_i) being the spatial location of the *i*-th city (geographic center of gravity coordinate), $\beta_{k_{(\mu_i, v_i)}}$ being the correlation between the variables of the *i*-th city, and ϵ_i being the error of the regression equation, GWR is calculated as follows [93]:

$$Y_i = \beta_{0_{(\mu_i,\ v_i)}} + \sum_k \beta_{k_{(\mu_i,\ v_i)}} X_{ik} + \epsilon_i \tag{8}$$

2.3.5. GeoDetector

In this study, GeoDetector is used to measure the interaction between different factors. Different factors interact with each other when they act together in the UPGA planning, and GeoDetector measures the interaction effect of factor pairs using the q-index. It calculates the spatial pattern of the dependent variable Y_i and the similarity of independent variables X_{ik} and X_{il} to obtain the single-factor and dual-factor influences q (X_i), q (X_j), and q ($X_i \cap X_j$); furthermore, it compares q ($X_i \cap X_j$) and other parameters to select and identify the final result—nonlinear weaken (q ($X_i \cap X_j$) < Min q (X_i), q (X_j)), single weaken (Min (q (X_i), q (X_j) < q ($X_i \cap X_j$) < Max q (X_i), q (X_j)), double enhance (q ($X_i \cap X_j$) > Max q (X_i), q (X_j)), independent (q ($X_i \cap X_j$) = q (X_i) + q (X_j)), and nonlinear enhance (q ($X_i \cap X_j$) > q (X_i) + q (X_j)) [94,95]. With h = 1, 2, 3, . . . *l*, where *l* is the number of partitions of spatial clustering, σ^2 is the total variance of dependent variables, σ_h^2 is the variance of dependent variables of the *h*-th partition, and *SSW* and *SST* are the sums of variances within the partition and the study area, the index *q* is calculated as follows [96]:

$$q = 1 - \frac{\sum_{h=1}^{l} n_h \sigma_h^2}{n\sigma^2} = 1 - \frac{SSW}{SST},\ \ SSW = \sum_{h=1}^{l} n_h \sigma_h^2,\ SST = n\sigma^2 \tag{9}$$

2.3.6. Ratio of Land Consumption Rate to Population Growth Rate (LCRPGR)

The *Transforming Our World—the 2030 Agenda for Sustainable Development* proposes 17 SDGs (sustainable development goals). Indicator SDG 11.3.1 is defined as the ratio of the Land Consumption Rate (LCR) to the Population Growth Rate (PGR) and is used to represent the relationship between urban expansion and population change [97]. This study chooses to use this method to evaluate the performance of UPGAs from a sustainable development perspective. LCR is a reflection of the growth rate of land used for urban park purposes and represents the efficiency of changes in the supply of urban green areas. PGR reflects the change rate of urban population and is used to measure the change rate of the green area demand of the population in an area over a period of time. LCRPGR measures the relationship between the change rates of two variables, LCR and PGR, and is used to represent the match between supply and demand in UPGAs. Theoretically, an LCRPGR equal to 1 is the most desirable result, and in view of the elasticity in practice development, 0.75 and 1.25 are set as thresholds to classify the analysis results into eight categories (Table 3). LCRPGR is calculated as follows [98]:

$$LCRPGR = \frac{LCR}{PGR} = \frac{\frac{\ln\left(UPG_i / UPG_i'\right)}{n}}{\frac{\ln\left(PD_i / PD_i'\right)}{n}} \tag{10}$$

Table 3. Matching relationship between urban park green space supply and population demand based on LCRPGR measurements.

Type	LCR	PGR	LCRPGR
Super oversupply	>0	<0	<0
Super undersupply	<0	>0	<0
Negative oversupply	<0	<0	>0 and <0.75
Negative undersupply	<0	<0	≥1.25
Negative equilibrium	<0	<0	>0.75 and <1.25
Positive oversupply	>0	>0	≥1.25
Positive undersupply	>0	>0	>0.75 and <1.25
Positive equilibrium	>0	>0	>0 and <0.75

3. Results

3.1. Spatiotemporal Evolution Model

3.1.1. Supply Scale

According to the relative share of supply scale of UPGAs, the coefficient of variation and Moran's I are 1.47 and 0.05, respectively (Z = 1.90, $p < 0.05$), indicating huge inter-city differences and significant positive spatial autocorrelation. Most of the high-value cities are concentrated in Shandong, Beijing, Tianjin, and provincial capital metropolitan areas such as Zhengzhou, Hefei, Hangzhou, Shijiazhuang, and Nanjing. The Nanjing metropolitan area extends to cover the region of Southern Jiangsu (Suzhou, Wuxi, Changzhou, etc.). In addition, Ningbo, Linyi, Yantai, Wuxi, Nantong, Luoyang, and Zibo also have a leading edge, with a relative share of over 10%. Most of the low-value cities are concentrated in the north and south of Hebei and Henan and in the west of Anhui and Zhejiang, especially Zhoushan, Jinhua, Hengshui, Tongling, Lu'an, Xuchang, Xinxiang, Anyang, Xinyang, Puyang, Suzhou, Zhumadian, Hebi, Cangzhou, Sanmenxia, Zhoukou, Bozhou, Quzhou, Xuancheng, Huangshan, Chizhou, and Lishui, and have a large disadvantage, with a relative share of not more than 3%. The hotspots are concentrated in Beijing, Tianjin, and the north of Hebei Province; the sub-hotspots are in the Shandong Peninsula and the densely populated urban areas of Southern Jiangsu; and most of the coldspots are located in the border areas of Henan, Anhui, Shandong, and Jiangsu Provinces (Figure 3).

According to the growth of UPGA supply scale, the CV and Moran's I are 0.70 and 0.01 (Z = 0.61, $p > 0.05$), respectively, indicating that neither the inter-urban differences nor the spatial correlations are significant. High-value cities are not spatially clustered geographically, and include Nantong, Fuyang, Zhengzhou, Wenzhou, Jining, Kaifeng, Ningbo, Chuzhou, Shangqiu, Yancheng, Taizhou, Qingdao, Suqian, and Liaocheng. Most of the low-value areas are clustered in northern Hebei and southeastern Shandong, with Pingdingshan, Luohe, Xinxiang, Qinhuangdao, Rizhao, Huaibei, Wuxi, Handan, Chizhou, Zhenjiang, Zhangjiakou, and Tangshan lagging behind in development, and Chengde in particular showing negative growth. The hotspot cities are mainly in the border areas of Henan, Anhui, and Shandong Provinces and extend to central Jiangsu. The sub-hotspot cities are distributed in the periphery of the hotspot cities in a "center-edge" structure. In southeastern Zhejiang, a small "center-edge" structure is developing. The coldspots are concentrated in Beijing, Tianjin, northern Hebei Province, central Shandong Province, and the border areas of Anhui and Zhejiang Provinces.

According to the spatiotemporal evolution model of the scale of UPGA supply, the median relative share and growth rates are 4.66% and 68.92%, respectively. A high proportion is found in HH and LL cities, both at approximately 30%. HH cities are scattered in distribution and are only in western Shandong; coastal Jiangsu; and the provincial capital metropolitan areas of Henan, Anhui, and Zhejiang, including Beijing, Tianjin, Xingtai, Changzhou, and others. LL cities are relatively clustered in the north of Hebei, the south of Anhui, the west of Zhejiang, and the northeast corner of Henan, including Zhangjiakou, Chengde, Cangzhou, Langfang, Zhenjiang, Jiaxing, Jinhua, Quzhou, Zhoushan, Lishui, Ma'anshan, Huaibei, Huangshan, Lu'an, Chizhou, Xuancheng, Zaozhuang, Rizhao, Binzhou, Pingdingshan, Anyang, Hebi, Xinxiang, Puyang, Luohe, and Xinyang. Most of the HL cities are concentrated in Shandong, Hebei, and Jiangsu, including Shijiazhuang, Tangshan, Qinhuangdao, Handan, Baoding, Nanjing, Wuxi, Xuzhou, Suzhou, Yangzhou, Huzhou, Taizhou, Huainan, Zibo, Yantai, Weifang, and Linyi. Most LH cities are concentrated in Henan and Anhui, especially in the border areas of the two provinces, including Hengshui, Taizhou, Suqian, Bengbu, Tongling, Anqing, Chuzhou, Suzhou, Bozhou, Heze, Kaifeng, Jiaozuo, Xuchang, Sanmenxia, Shangqiu, Zhoukou, and Zhumadian. Overall, most of the hotspot cities are clustered in the west of Shandong and extend to Jiangsu and Hebei, while most of the coldspot cities are in the central part of Henan and the border area of Anhui and Zhejiang, both geographically distributed in a band (Figure 4).

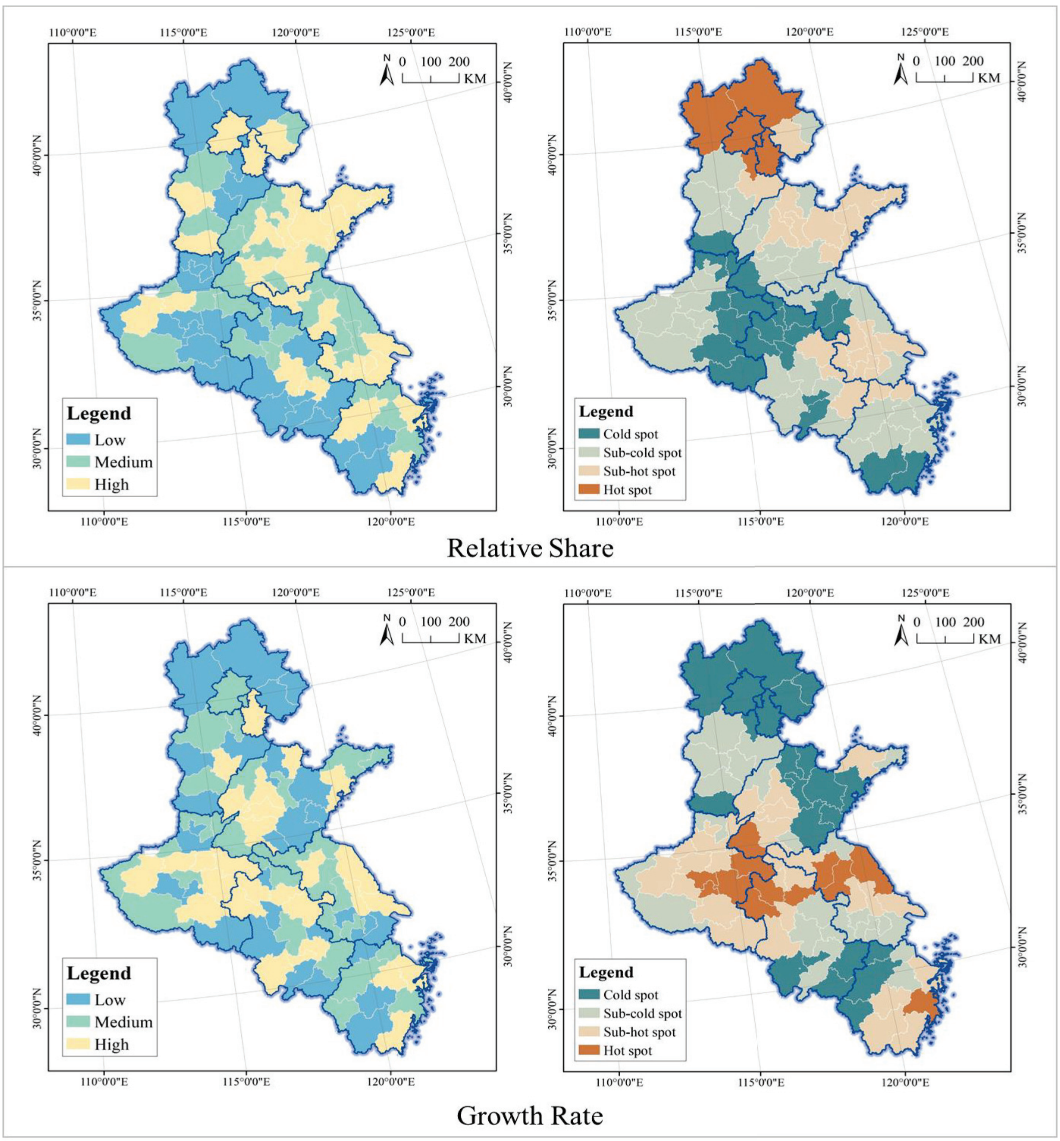

Figure 3. Relative share and growth rate spatial analysis of the supply scale of UPGAs in the Grand Canal of China.

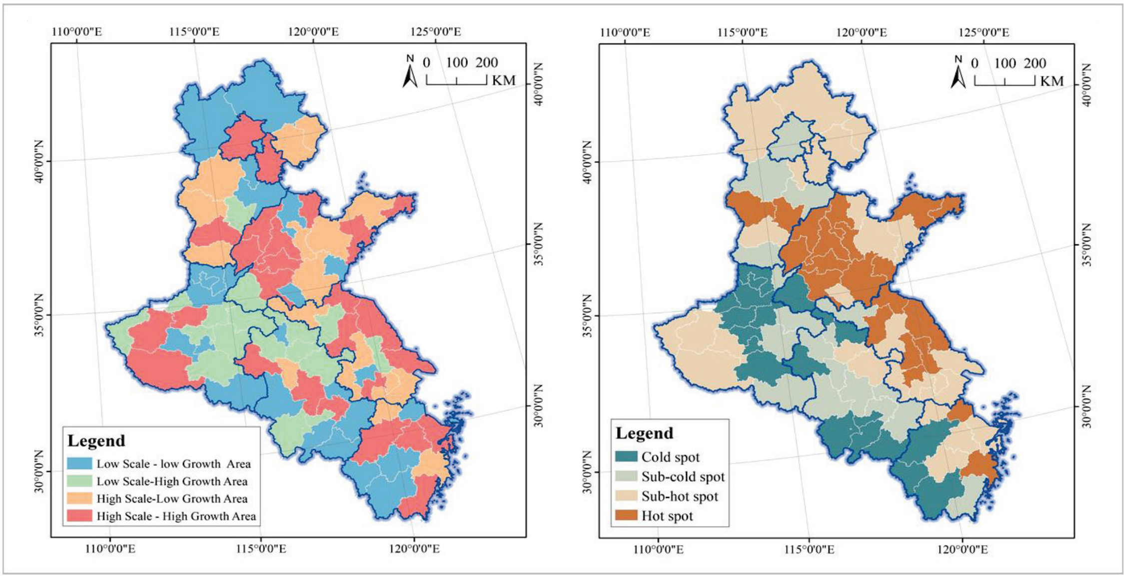

Figure 4. Spatiotemporal evolution model of the supply scale of urban park green areas on the Grand Canal of China.

3.1.2. Per-Capita Area

According to the relative share of the per-capita area of UPGAs, the CV and Moran's I are 0.19 and 0.17, respectively ($Z = 3.93$, $p < 0.01$), indicating moderate inter-city differences but significant positive spatial autocorrelation. Most of the high-value cities are concentrated in Shandong, with a few in the northern end of Hebei and southern Anhui. In addition, Chuzhou, Bozhou, Fuyang, Nantong, Yangzhou, and other cities also have a leading edge, with a relative share close to 70%. Most of the low-value cities are concentrated in Zhejiang, the western part of Hebei, the border area of Henan and Shandong, and the central part of Anhui, especially Taizhou, Wuhu, Pingdingshan, Hefei, Anyang, Suzhou, Jinhua, Hangzhou, Xinxiang, Jinan, Lishui, Cangzhou, Zhangjiakou, and Tianjin, and they have a significant disadvantage, with a relative share of less than 50%. The hotspot cities are all clustered in Shandong and the sub-hotspot cities are in its periphery and extend to Hebei and Jiangsu, forming a "center-edge" structure. There are three clusters of coldspot cities in Zhejiang (except Hangzhou), Beijing–Tianjin, and the east of Henan, while all other cities are sub-hotspots (Figure 5).

According to the growth rate of the per-capita area of UPGAs, the CV and Moran's I are 1.17 and 0.20 ($Z = 4.53$, $p < 0.01$), respectively, indicating significant spatial heterogeneity and spatial autocorrelation. Most of the high-value cities are concentrated in Henan and extend in a continuous belt towards Anhui and a necklace (stepping stone) towards Shandong. Low-value cities are clustered in northern Hebei, central Zhejiang, Shandong, and southern Jiangsu, with Zhangjiakou, Shaoxing, Hefei, Qinhuangdao, Yantai, Handan, Rizhao, Hangzhou, Chengde, and Suzhou in particular showing negative growth. The hotspot cities are mainly concentrated in the border area of Henan and Anhui Provinces, while the sub-hotspot cities are in its periphery, forming a "center-edge" structure. There are three coldspot urban clusters in northern Zhejiang, the peninsula and south of Shandong, and the eastern part of the Beijing–Tianjin–Hebei metropolitan area (Beijing–Tangshan–Qinhuangdao region).

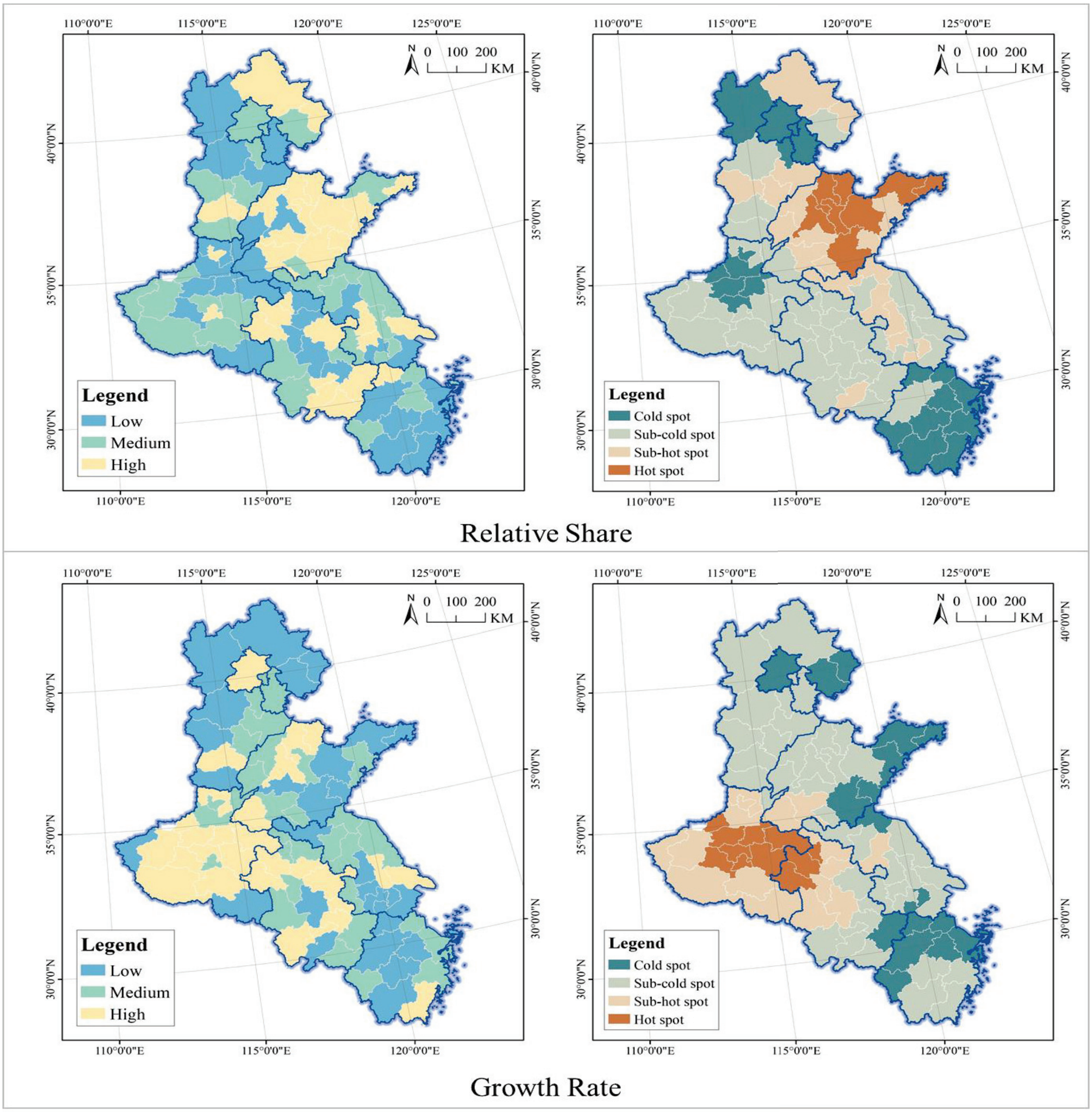

Figure 5. Relative share and growth rate spatial analysis of the per-capita area of UPGAs in the Grand Canal of China.

According to the spatiotemporal evolution model of per-capita area of UPGAs, the median relative share and growth rate are 59.33% and 22.86%, respectively. A high proportion is found in HL and LH cities, both at approximately 25%. HH cities are dispersed in a geographical distribution, including Xingtai, Langfang, Nantong, Taizhou, Suqian, Quzhou, Huaibei, Tongling, Chuzhou, Fuyang, Lu'an, Bozhou, Qingdao, Beijing, Zibo, Dongying, Jining, Binzhou, Luoyang, and Xuchang. Most of the LL cities are concentrated in Hebei and Zhejiang, a small number are located in the densely populated urban areas of southern Jiangsu, and very few are randomly distributed. LL cities include Tianjin, Shijiazhuang, Baoding, Zhangjiakou, Cangzhou, Wuxi, Changzhou, Suzhou, Hangzhou, Jiaxing, Shaoxing, Jinhua, Taizhou, Lishui, Hefei, Huainan, Zaozhuang, Liaocheng, Puyang, and Xinyang. Most of the HL cities are concentrated in Shandong, and there are two small clusters in the southern end of Anhui and the northeast corner of Hebei. These include Tangshan, Qinhuangdao, Handan, Chengde, Nanjing, Xuzhou, Yangzhou, Zhenjiang, Huzhou, Zhoushan, Huangshan, Chizhou, Xuancheng, Yantai, Weifang, Tai'an, Weihai, Rizhao, Linyi, Dezhou, Hebi, Luohe, and Sanmenxia. Most of the LH cities are concentrated in Henan and extend to northern Anhui and northern Jiangsu, including Hengshui, Lianyungang, Huai'an, Yancheng, Ningbo, Wenzhou, Wuhu, Bengbu, Ma'anshan, Anqing, Suzhou, Jinan, Heze, Zhengzhou, Kaifeng, Pingdingshan, Anyang, Xinxiang, Jiaozuo, Nanyang, Shangqiu, Zhoukou, and Zhumadian. Overall, most of the hotspot cities are clustered in Shandong; sub-hotspot cities are mostly found in Henan, Anhui, Jiangsu, Hebei, Beijing, and Tianjin; most of the coldspot cities are in Zhejiang; and most of the sub-coldspot cities are in the border areas of Hebei, Henan, and Shandong, showing significant clustering characteristics (Figure 6).

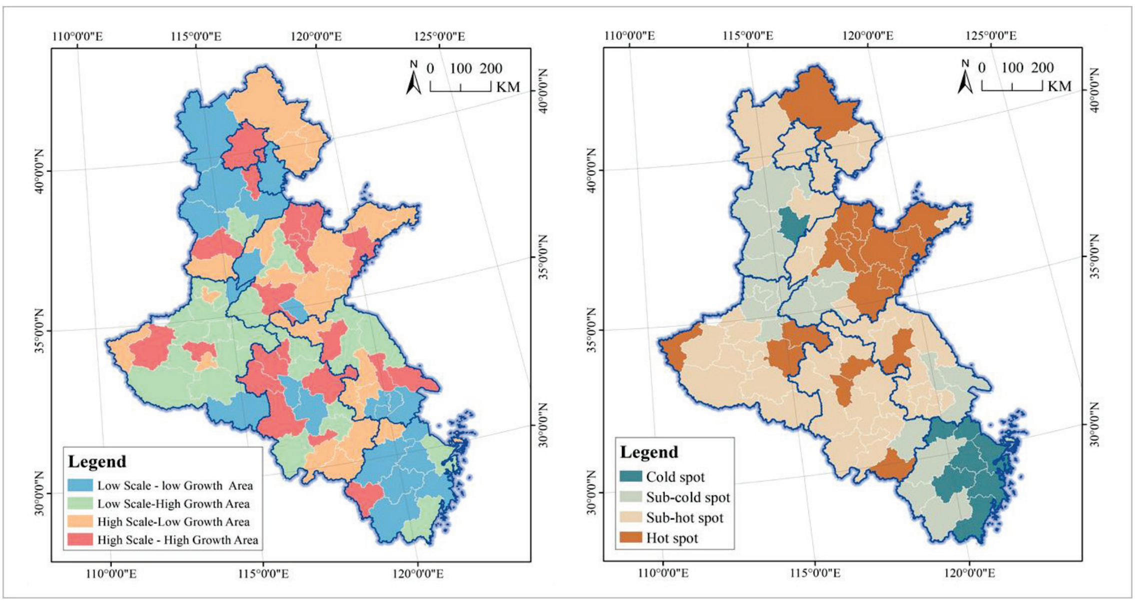

Figure 6. Spatiotemporal evolution model of the Ppr-capita area of urban park green areas on the Grand Canal of China.

The comparative analysis in the above two dimensions shows that Anyang, Pingdingshan, Puyang, Shangqiu, Xinyang, and Zhengzhou are always at a low level in the supply and per-capita area of urban green areas, with the construction of urban green infrastructure far behind that of other cities along the Grand Canal. Therefore, more investment and support are needed in future planning, construction, and management. On the contrary, Qingdao, Linyi, Nantong, Zibo, Weifang, Jining, Weihai, and Dongying are consistently at a high level, with the urban green infrastructure development ahead of the other cities in the Grand Canal, making them of exemplary value in the region. It should be noted that historical and cultural cities and livable cities such as Hangzhou, Beijing, Nanjing, Tianjin, and Suzhou are regional leaders in the scale of urban green areas supply, but they have no competitive advantage per capita. They should attach special attention and focus to green infrastructure planning, construction, and management in the future.

3.2. Driving Mechanism

3.2.1. Importance and Nature of Factors

The analysis results from the machine learning regression algorithms show a high goodness, generally greater than 0.85, with decision tree being optimal in both schemes. The results of the four algorithms are in general similar. Although there are differences in the coefficients of factors with higher and lower importance, their ranking remains relatively stable (Table 4). To provide full play to the advantages of all algorithms and eliminate the defects of a single algorithm, this paper uses the average values of four algorithms to determine the importance of factors. For the supply scale of UPGAs, topography, outflow population, and population density have much higher importance than other factors, and they are defined as key factors; fiscal self-sufficiency rate and average temperature have much lower importance than other factors, and they are defined as auxiliary factors with direct influences that can be ignored; and ventilation coefficient, proportion of population aged 60 and above, GDP, and per-capita GDP are not more or less important and are defined as important factors. For per-capita area of UPGAs, per-capita GDP is a key factor; fiscal self-sufficiency rate, GDP, and average temperature are auxiliary factors; while topography, ventilation coefficient, population density, outflow population, and proportion of population aged 60 and above are important factors (Figure 7).

Table 4. Machine learning regression results based on different algorithm analysis of urban park green areas on the Grand Canal of China. The asterisk represents the result after rounding.

Factors	Supply Scale of UPGAs				Per-Capita Area of UPGAs			
	Decision Tree	Random Forest	Adaboost	Extra Trees	Decision Tree	Random Forest	Adaboost	Extra Trees
X_1	13.00%	5.90%	6.70%	7.60%	24.70%	13.50%	12.00%	12.80%
X_2	4.80%	7.30%	8.80%	5.80%	7.10%	6.70%	7.90%	10.10%
X_3	3.30%	7.40%	11.40%	8.70%	19.50%	18.00%	16.90%	13.50%
X_4	3.10%	5.50%	6.70%	6.00%	3.00%	7.70%	10.20%	8.40%
X_5	57.40%	47.50%	29.60%	28.10%	4.60%	4.90%	8.20%	10.10%
X_6	0.00%	5.00%	6.80%	10.50%	0.90%	6.30%	7.70%	10.80%
X_7	7.40%	10.50%	13.70%	15.00%	33.00%	22.00%	18.60%	13.10%
X_8	0.00%	3.60%	6.80%	7.60%	4.20%	6.00%	5.50%	6.70%
X_9	10.80%	7.20%	9.50%	10.70%	3.00%	14.80%	13.00%	14.60%
R^2	1 *	0.89	1 *	0.90	1 *	0.87	0.99	0.86

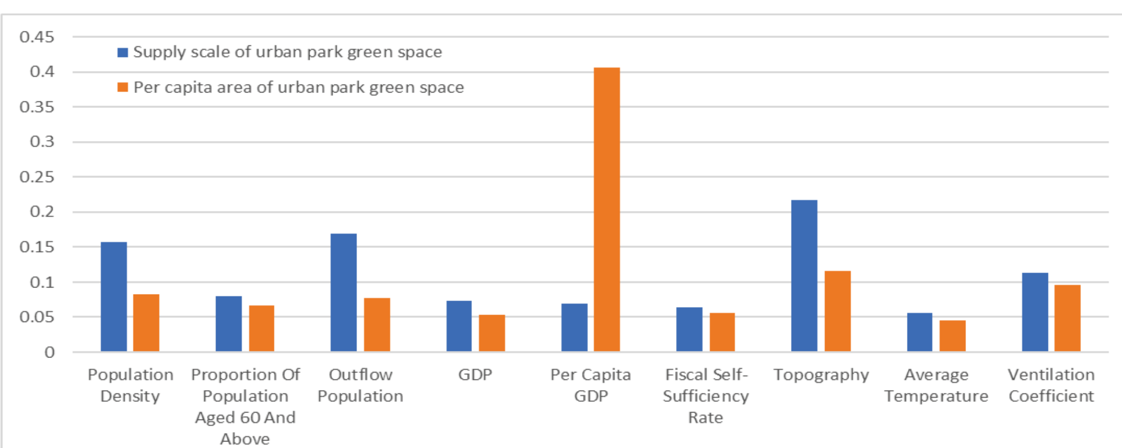

Figure 7. Factor importance analysis of UPGAs in the Grand Canal of China.

3.2.2. Spatial Effect of Factors

From the supply scale of UPGAs, the minimum values of proportion of population aged 60 and above (X_2), GDP (X_4), and fiscal self-sufficiency rate (X_6) are all greater than zero, suggesting that they all play a positive role as a whole. The maximum values of topography (X_7), average temperature (X_8), and ventilation coefficient (X_9) are all less than zero, suggesting that they all act as negative obstacles overall. The maximum values of population density (X_1), output population (X_3), and per-capita GDP (X_5) are greater than zero, while the minimum values are less than zero, indicating that they both have positive driving and negative blocking effects with a complex impact mechanism (Table 5). The influence of population density shows a "dumbbell" pattern geographically, decreasing from the north and south to the middle. Beijing, Tianjin, and Hebei in the north are highlands of positive effects, while Henan is a depression of negative effects and Zhejiang is a new highland of positive effects. The proportion of population aged 60 and above is characterized by coastal highs and inland lows, with Bohai Bay (Beijing, Tianjin, Hebei, Shandong) as the high ground, the Yangtze River Delta as the second high ground, and Henan and Anhui as the depressions, with the weakest in Henan. The influence of the outflow population also presents a "dumbbell" pattern geographically, with the Yangtze River Delta, especially Zhejiang and southern Anhui Provinces, being the highlands of positive effects and Beijing–Tianjin–Hebei being the highlands of negative effects. The depressions are distributed in the border areas of Henan, Shandong, Anhui, and Jiangsu Provinces. The highland of GDP influence is in the west of Anhui and the south of Henan, and it is the origin of the gradient to the north and the coast, reaching the lowest in the Beijing–Tianjin–Hebei region. Per-capita GDP is characterized by a decreasing gradient from south to north, with highlands in Zhejiang and southern Anhui and depressions in Bohai Bay and the Shandong Peninsula. The fiscal self-sufficiency rate has a high impact on the northern region, with Beijing and Hebei as the highlands, and low for the center, with Anhui and the northern border region of Jiangsu as the depressions. The influence increases in a gradient from the depression to the south and reaches the highest in Zhejiang. The influence of topography, average temperature, and ventilation coefficient is characterized by clustering, and the depressions are all located in the Yangtze River Delta, especially in the southern part of Zhejiang and Anhui Provinces. Their highlands are all clustered in bands, but with differences in geographic location, where topography is located in the Shandong Peninsula, the average temperature is located in the junction area of Shandong, Henan, Anhui, and Jiangsu Provinces, and the ventilation coefficient is in the north of Henan and the west of Hebei (Figure 8).

From the per-capita area of UPGAs, only the minimum value of per-capita GDP (X_5) is greater than zero, indicating that it plays a positive driving role. The maximum values of outflow population (X_3), GDP (X_4), topography (X_7), average temperature (X_8), and ventilation coefficient (X_9) are all less than zero, suggesting that they all act as negative obstacles overall. The maximum values of population density (X_1), proportion of population aged 60 and above (X_2), and fiscal self-sufficiency rate (X_6) are greater than zero, while the minimum values are less than zero, indicating that they both have positive driving and negative blocking effects with a complex impact mechanism (Table 6). The influence of population density is characterized by a geographic gradient of "high in the coastal area and low in the inland area", with the two clusters in the Shandong Peninsula and the northern end of Hebei being the highlands, and the contiguous band-like areas in Henan, Anhui, and western Zhejiang being the depressions. The influence of the proportion of population aged 60 and above presents a "dumbbell" pattern geographically, with the Yangtze River Delta as the highland of positive influence and Beijing–Tianjin–Hebei as the highland of negative influence, divided by the border area of Henan, Shandong, and Hebei. The influence of the outflow population is geographically characterized by "high in the north and low in the south", with Beijing–Tianjin–Hebei being the highland and the Yangtze River Delta being the depression. The influence of GDP is characterized by a geographic gradient of "high in the inland area and low in the coastal area", with the highlands located in the border area between Anhui and Henan and the depressions in the Shandong Peninsula and the east coast of Zhejiang. Per-capita GDP and outflow population are highly similar in their geographic patterns of influence, except that the nature of the influence shifts from negative to positive. The influence of the fiscal self-sufficiency rate, the proportion of population aged 60 and above, and topography is geographically characterized by a "low in the center and high at the edge", with depressions located in the border areas of Anhui, Henan, Shandong, and Jiangsu and highlands in the Shandong Peninsula, both with a small spatial scale. The average temperature influence highland is located in the border areas of Zhejiang, Anhui, and Jiangsu Provinces, and the depression is in Henan. The geographic pattern of influence of ventilation coefficient and outflow population is similar; however, the coverage of the latter uplands and depressions is larger than that of the latter, with highlands extending to the north and west of Henan and depressions expanding to the south of Jiangsu and the south of Anhui (Figure 9).

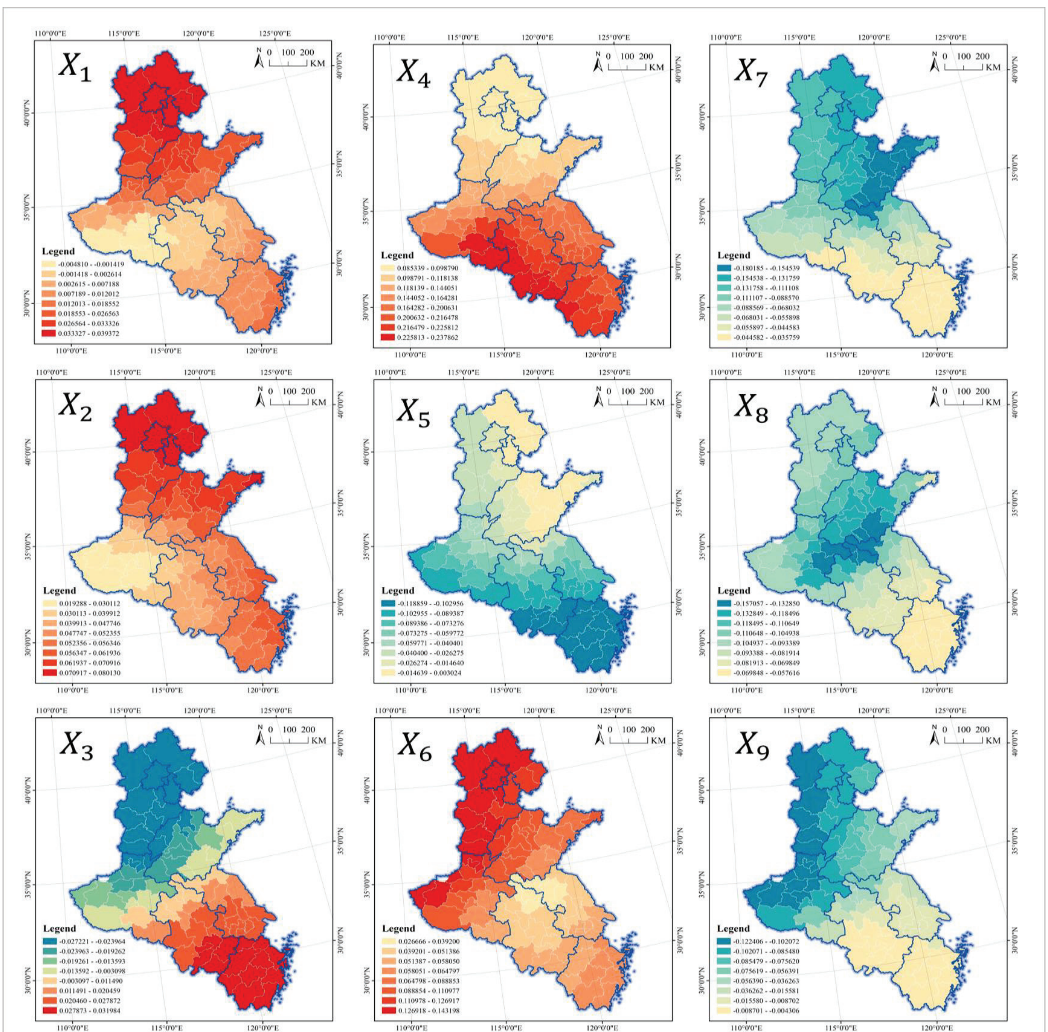

Figure 8. Factor spatial effect analysis of the supply scale of urban park green areas on the Grand Canal of China.

Table 5. Descriptive statistical analysis of GWR parameters for the supply scale of urban park green areas on the Grand Canal of China.

Factors		Min	25% Quantile	Median	75% Quantile	Max
Population density	X_1	−0.0048	0.0043	0.0105	0.0241	0.0394
Proportion of population aged 60 and above	X_2	0.0193	0.0453	0.0541	0.0599	0.0801
Outflow population	X_3	−0.0272	−0.0220	−0.0049	0.0265	0.0320
GDP	X_4	0.0853	0.1141	0.1914	0.2162	0.2379
Per-capita GDP	X_5	−0.1189	−0.0948	−0.0622	−0.0253	0.0030
Fiscal self-sufficiency rate	X_6	0.0267	0.0534	0.0642	0.1181	0.1432
Topography	X_7	−0.1802	−0.1270	−0.0838	−0.0478	−0.0358
Average temperature	X_8	−0.1571	−0.1136	−0.1051	−0.0777	−0.0576
Ventilation coefficient	X_9	−0.1224	−0.0918	−0.0458	−0.0093	−0.0043

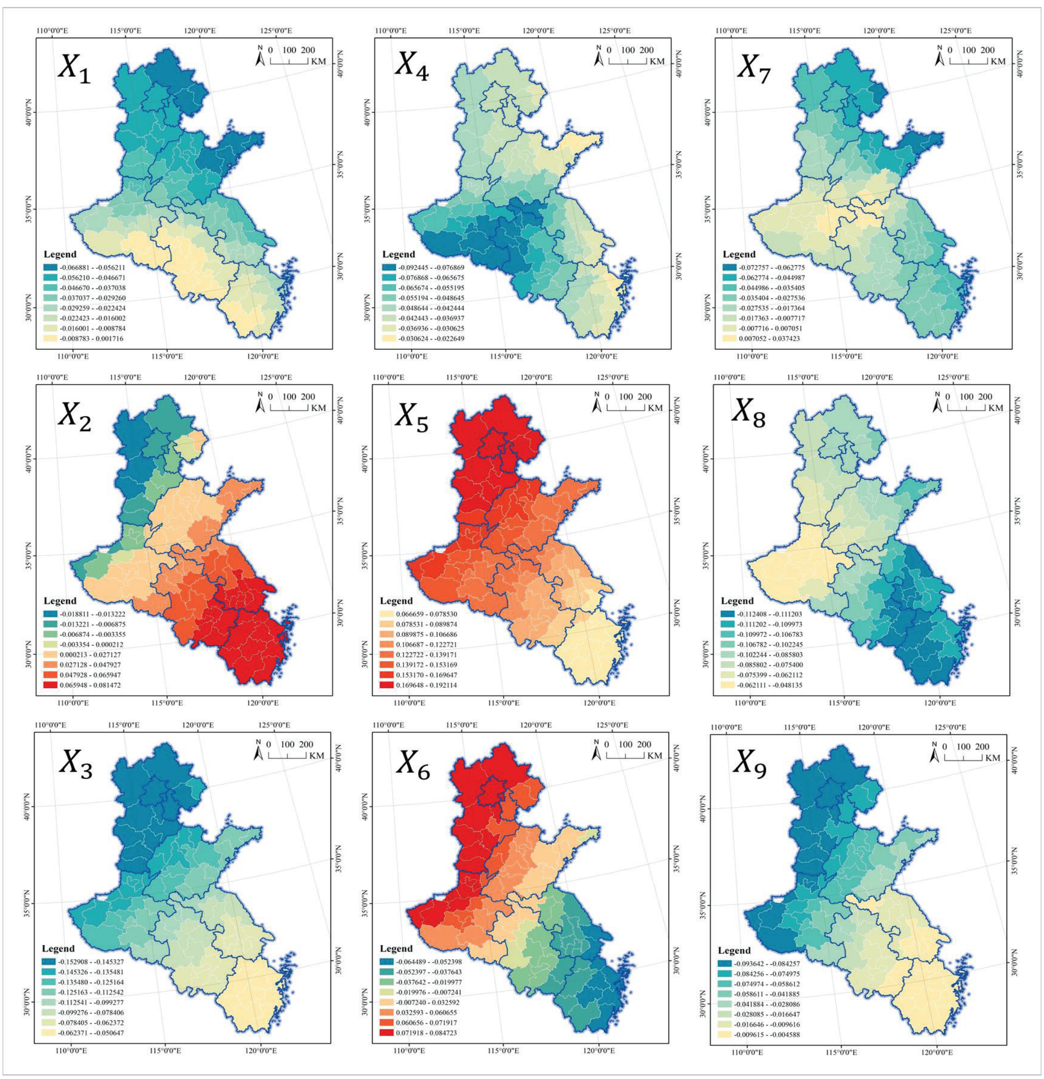

Figure 9. Factor spatial effect analysis of the per-capita area of urban park green areas on the Grand Canal of China.

Table 6. Descriptive statistical analysis of GWR parameters for the per-capita area of urban park green areas on the Grand Canal of China.

Factors		**Min**	**25% Quantile**	**Median**	**75% Quantile**	**Max**
Population density	X_1	0.4871	0.5163	0.5195	0.5213	0.5392
Proportion of population aged 60 and above	X_2	−0.0669	−0.0463	−0.0303	−0.0164	0.0017
Outflow population	X_3	−0.0188	0.0008	0.0335	0.0671	0.0815
GDP	X_4	−0.1529	−0.1385	−0.1140	−0.0711	−0.0506
Per-capita GDP	X_5	−0.0924	−0.0607	−0.0462	−0.0397	−0.0226
Fiscal self-sufficiency rate	X_6	0.0667	0.0951	0.1320	0.1579	0.1921
Topography	X_7	−0.0645	−0.0369	0.0147	0.0683	0.0847
Average temperature	X_8	−0.0728	−0.0352	−0.0251	−0.0099	0.0374
Ventilation coefficient	X_9	−0.1124	−0.1106	−0.0939	−0.0724	−0.0481

3.2.3. Interactive Effect of Factors

Different factors show a significant synergistic enhancement effect, mainly in the form of nonlinear enhancement, with only a few factor pairs in double enhancement. For the supply scale of UPGAs, the factor pair of topography ∩ average temperature ($X_7 \cap X_8$) is in double enhancement. For the per-capita area of UPGAs, population density ∩ proportion of population aged 60 and above ∩ proportion of population aged 60 and above ($X_1 \cap X_2$), population density ∩ GDP ($X_1 \cap X_4$), proportion of population aged 60 and above ∩ GDP ($X_2 \cap X_4$), and proportion of population aged 60 and above ∩ average temperature ($X_2 \cap X_8$) are in double enhancement. It is worth noting that a large number of super-factor pairs arise from factor interaction, and their interaction forces are much higher than those of other factor pairs and single factors. Population density ∩ GDP ($X_1 \cap X_4$), proportion of population aged 60 and above ∩ GDP ($X_2 \cap X_4$), outflow population ∩ GDP ($X_3 \cap X_4$), per-capita GDP ∩ GDP ($X_5 \cap X_4$), and ventilation coefficient ∩ GDP ($X_9 \cap X_4$) are super factor pairs of the supply scale of UPGAs, with an interaction force of more than 0.80. Population density ∩ per-capita GDP ($X_1 \cap X_5$), outflow population ∩ Per-capita GDP ($X_3 \cap X_5$), outflow population ∩ average temperature ($X_3 \cap X_8$), outflow population ∩ ventilation coefficient ($X_3 \cap X_9$), per-capita GDP ∩ average temperature ($X_5 \cap X_8$), and per-capita GDP ∩ ventilation coefficient ($X_5 \cap X_9$) are super factor pairs of the per-capita area of UPGAs, with an interaction force of more than 0.5 (Table 7).

Table 7. Factor interactive effect analysis of urban park green areas on the Grand Canal of China.

	Code	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
Supply scale of UPGAs	X_1	0.08								
	X_2	0.54	0.12							
	X_3	0.63	0.63	0.28						
	X_4	**0.84**	**0.80**	**0.84**	0.45					
	X_5	0.61	0.67	0.56	**0.87**	0.26				
	X_6	0.62	0.63	0.65	0.78	0.57	0.25			
	X_7	0.15	0.19	0.43	0.52	0.34	0.33	0.00		
	X_8	0.27	0.35	0.42	0.69	0.38	0.41	0.08	0.05	
	X_9	0.53	0.56	0.69	**0.82**	0.64	0.76	0.16	0.31	0.12
Per-capita area of UPGAs	X_1	0.03								
	X_2	0.09	0.05							
	X_3	0.49	0.36	0.19						
	X_4	0.06	0.07	0.25	0.01					
	X_5	**0.52**	0.34	**0.69**	0.33	0.20				
	X_6	0.28	0.14	0.38	0.12	0.33	0.06			
	X_7	0.11	0.11	0.47	0.07	0.38	0.14	0.02		
	X_8	0.30	0.24	**0.56**	0.25	**0.62**	0.38	0.30	0.18	
	X_9	0.21	0.21	**0.55**	0.11	**0.52**	0.17	0.08	0.35	0.03

3.3. Performance Evaluation

No cities in the Grand Canal region fall into the categories of negative oversupply, negative undersupply, or negative equilibrium. Positive oversupply has the highest proportion, more than 50%, followed by positive equilibrium at approximately 30%. Ma'anshan, Huaibei, Binzhou, Luoyang, Pingdingshan, and Shangqiu are super oversupply members. The only member of the super undersupply group is Chengde, while the only member of the positive undersupply group is Handan. The positive oversupply members include Beijing, Tangshan, Xingtai, Cangzhou, Langfang, Hengshui, Nanjing, Nantong, Lianyungang, Huai'an, and others. Most of these are clustered in Henan and Anhui and extend in a band towards Jiangsu, Zhejiang, and Hebei. The positive equilibrium members include Tianjin, Shijiazhuang, Qinhuangdao, Baoding, Zhangjiakou, Wuxi, Xuzhou, and others. These are distributed in bands in Shandong and Hebei and in clusters in Jiangsu and Zhejiang. Overall, there are three clusters of hotspot cities in Shandong, Jiangsu, and Zhejiang and three clusters of coldspot cities in Henan, the northern end of Hebei, and the border area between Henan and Anhui, with sub-hotspots and sub-coldspots distributed on their periphery, forming a "center-edge" spatial structure (Figure 10).

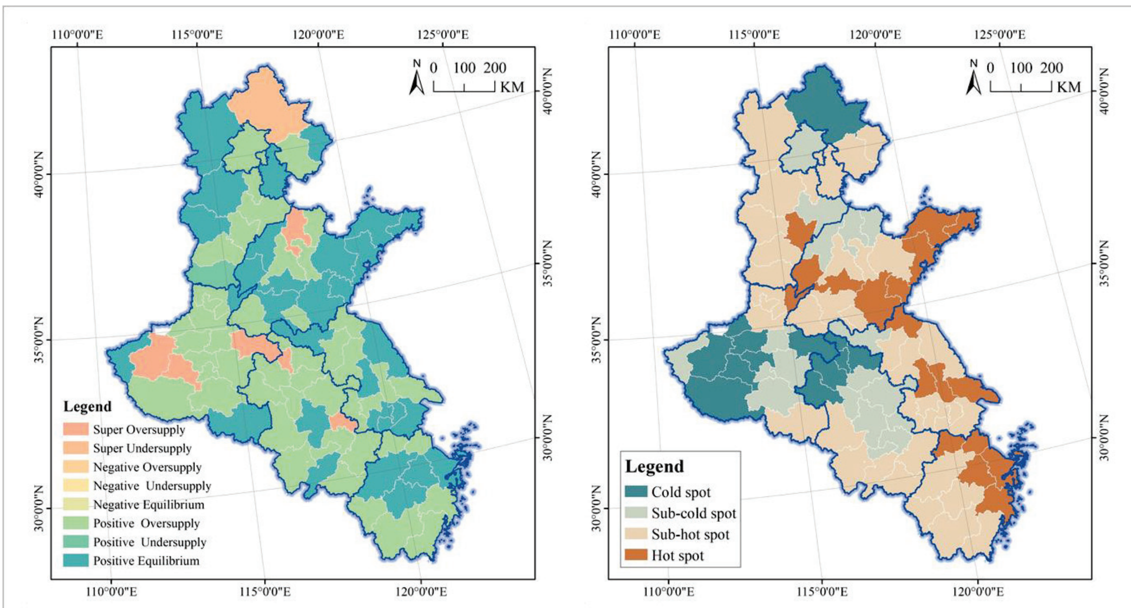

Figure 10. Performance analysis of urban park green areas on the Grand Canal of China.

4. Discussion

4.1. Differentiated Zoning Planning

The study shows significant spatial inequalities and differences in the geographic distribution of UPGAs in the Grand Canal, with huge disparities in the supply scale and per-capita area across cities, including relative shares, growth rates, and spatial and temporal evolution patterns. In addition, most of the UPGA supply is in a mismatch with the population demand, with co-existence of both oversupply and undersupply. The high similarity of these analytical results to the findings of other scholars suggests that spatial imbalances and inequalities, supply–demand imbalances, and mismatches are regular features. For the former, Rigolon [99] concluded that there are significant spatial inequalities in urban parkland and quality and Ren [100] found geographic and social inequalities in the distribution of urban parks in Shanghai based on Gini coefficient analysis.

For the latter, Tan [101], Gao [102], and Zhu [103] in their case studies of Wuhan, Shenzhen, and Beijing found that there is a serious mismatch between UPGA supply and resident demand, which is a great challenge for future planning and management. Unfortunately, current green areas planning, park planning, and green infrastructure planning focuses more on the design of spatial layout schemes for intra-city parks and green area systems, with less attention and planning response to inter-city imbalances and inequalities in general [104].

In summary, we recommend the adoption of differentiated zoning planning strategies in green areas and park planning for the Grand Canal. This takes the evaluation of the performance of matching supply and demand as the core basis to adjust the direction of the control of the supply scale and per-capita area in cities according to the classification results of the spatio–temporal evolution mode of urban parkland. For cities such as Tianjin, Shijiazhuang, Qinhuangdao, Baoding, Zhangjiakou, and Wuxi, as their supply and demand are in positive balance, the focus of their future planning will be to keep their management policies stable and to maintain and contribute to the city's long-term balance of supply and demand. Handan and Chengde face a serious supply shortage, with UPGA supply size and per-capita area in HL and LL states, resulting in weak growth. Therefore, in the future, provincial governments should increase the quota of their UPGAs, and city governments should adopt speed control-oriented planning and policies to accelerate incremental supply and promote a balance between supply and demand. For Tangshan, Xingtai, Cangzhou, Langfang, Hengshui, Nanjing, Nantong, Lianyungang, and other positive oversupply cities, subdivision planning based on spatio–temporal evolution patterns is required. Cities with spatio–temporal evolution patterns in the HH and LH categories, such as Xingtai, Nantong, Dongying, Fuyang, and Anqing, should strictly limit the growth of quotas in the future and promote a balance between supply and demand by reducing land supply. They should focus UPGA planning and management on quality improvement rather than quantity growth in the future, and they could sell their surplus land index to undersupply cities via the regional inter-city trading platform. Cities with spatio–temporal evolution in LL and HL patterns, such as Cangzhou, Tangshan, Jiaxing, Huzhou, Lishui, and Xuancheng, should increase or purchase land quotas and strengthen the planning, design, and management of urban green areas to promote a balance between supply and demand through the growth of land supply and the strict protection of the stock.

4.2. Integrated Symbiotic Planning

We found significant spatial correlations of UPGAs in the Grand Canal in this study, with hotspot and coldspot cities clustering together. It should be noted that Choumert [105] and Kim [106] also noted such correlations, and in common with this paper they both found significant positive spatial autocorrelations in UPGAs between cities in France and South Korea, with local spatial clustering features prominent, although the global correlation is weak or insignificant. However, unfortunately, they did not propose a response strategy for spatial planning and green area management policies based on spatial correlation characteristics. We believe that clustered hotspot and coldspot cities face similar development challenges, and they can maximize their performance with minimum cost through inter-city collaboration in UPGA planning and management. Highly interconnected cities may seek to rapidly increase the quantity and quality of their own and regional green infrastructure through the construction of point-like regional parks and linear inter-city greenways.

For the construction of regional parks, cities can learn from the European experience of building large-scale green parks across administrative districts based on the characteristics of natural resources such as the Grand Canal's green areas and water system, as well as planning and constructing open spaces, high-quality landscapes, and recreational and activity facilities to promote the symbiosis of spatial functions and social needs [107,108]. In urban green area system planning, park system planning, and green infrastructure planning in China, it is common to keep the planning scope in line with the scope of the city's overall planning, i.e., the planning is more confined to the central urban area, which has seriously weakened the overall allocation of green resources in counties and towns within the municipal area and has led to no overall planning for the regional green area system. The construction of regional parks that are not confined to the central city and encouraged coordination between neighboring cities will contribute to the integration of regional ecological, spatial, tourism, and social resources to enhance regional sustainability and competitiveness. The regional greenway is a linear green open space. Natural and artificial landscapes such as mountains, lakes, fields, scenic spots, ancient cities, cultural heritages, traditional villages, and tree-lined roads along the main stream and tributaries of the Grand Canal should be connected together, and landscape recreation routes and service facilities serving pedestrians and cyclists should be built within them [109]. Hotspot cities can link and showcase quality parks and green areas in the united cities through regional greenways to enhance the overall image of the regional habitat. For coldspot cities, they can promote the sharing of parks and green area resources among different cities through regional greenways to enhance utilization efficiency and alleviate, to a certain extent, the imbalance between supply and demand.

4.3. Multi-Policies Mix Management

Both the supply scale and per-capita areas of UPGAs have very complex driving mechanisms. In terms of nature, the ventilation coefficient always plays a negative blocking role, while population density always has both positive driving and negative blocking effects. The roles of other factors are always in a complex state of change and may shift from positive to negative (e.g., GDP), mixed (e.g., proportion of population aged 60 and above), or from negative to mixed (e.g., average temperature and topography) or from mixed to positive (e.g., per-capita GDP) and negative (e.g., outflow population). In terms of intensity, the key factors of supply scales of UPGAs are completely different from those of their per-capita area. Proportion of population aged 60 and above and ventilation coefficient are always important factors for both, while average temperature and fiscal self-sufficiency rate are always common auxiliary factors. The intensity ratings of the other factors differ widely. For example, GDP has been reduced from an important factor of the supply scale of UPGAs to an auxiliary factor of their per-capita area. Per-capita GDP, by contrast, has been upgraded from an important factor to a key factor. In terms of interaction, the super factor pairs of the supply scale of UPGAs are completely different from those of their per-capita area. In terms of spatial effects, all factors show a significant spatial clustering of influence on geographic patterns, but the geographic distribution and spatial extent of highlands and depressions vary widely, with a variety of change patterns such as gradient rise and fall, high in the center and low at the edge, low in the center and high at the edge, dumbbell (high at the ends and low in the middle), contiguous belt, and clustering emerging (Figure 11).

A growing body of research reveals that the planning and management of UPGAs are complex systematic projects subject to the influence of many factors. Many scholars have discussed the factors influencing changes in urban parks. For example, Cheng [110], Nam [111], and Smith [112] argued that government funding plays a key role in the management of urban parks in China and the United Kingdom. Luo [113], Feng [114], and Kim [115] argued that both population density and size had significant spatial correlations with the level of service of urban parks. Guo [116,117] found that house prices, transportation accessibility, and the status of the surrounding commercial facility package are important factors influencing the accessibility of urban parks. Their findings are corroborated with the conclusions of this paper. Different from them, this paper fully explores the spatial effects and interaction effects of different factors, which has a great inspirational value for the design of policy combination. In view of the intensity, nature, and spatial and interaction effects of different factors, future planners and the government should better interconnect the policies for UPGAs. Since a single policy is limited and difficult to operationalize in practice, multiple policies should be designed and implemented in the management. In addition, attention should be paid to the mode of combining policies in policy design and implementation, integrating policies on population, ageing, social mobility, economic and industrial development, financial investment, and the building of an ecological civilization. While ensuring the precision of each policy, it is important to maximize the synergy of different policies and to maximize policy performance by means of the interaction effect of factor pairs.

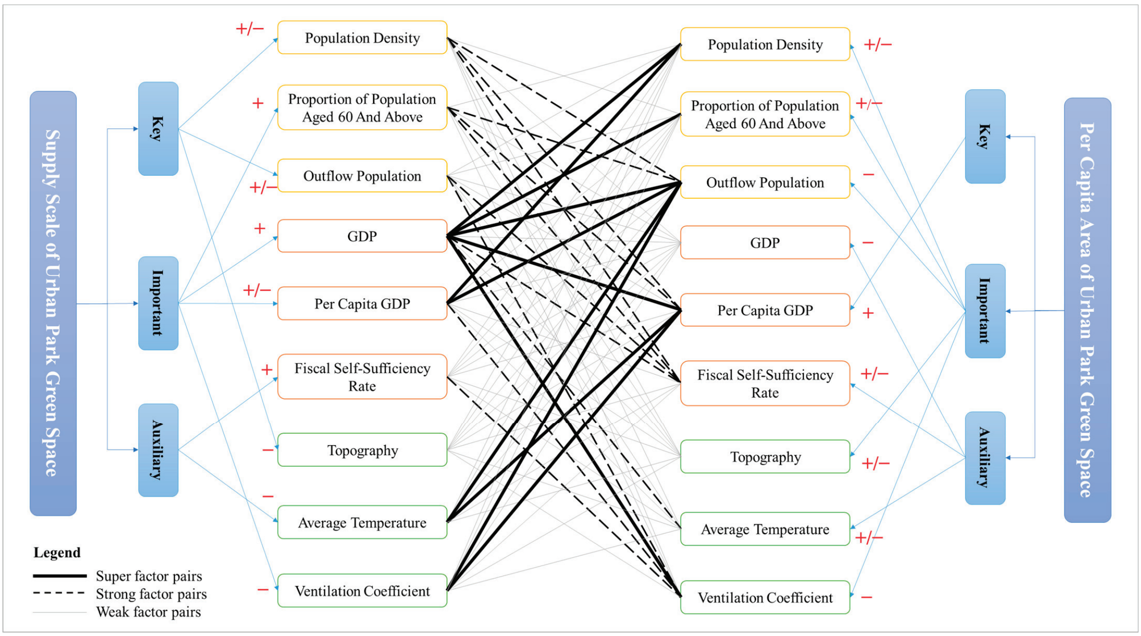

Figure 11. Factor spatial effect analysis of the urban park green areas on the Grand Canal of China.

5. Conclusions

This paper arrives at the following findings: (1) The spatio–temporal evolution patterns of the UPGAs in the Grand Canal of China are diversified, with many types emerging, such as HH (High-scale–High-growth), HL (High-scale–Low-growth), LH (Low-scale–High-growth), and LL (Low-scale–Low-growth). (2) The evolutionary performance of UPGAs in the Grand Canal is mainly characterized by positive oversupply and positive equilibrium, with super oversupply, super undersupply, and positive undersupply found in a small number of cities. (3) The spatio–temporal evolution patterns and performance of UPGAs are characterized by significant spatial heterogeneity and positive spatial autocorrelation, with huge inter-city differences, and both hotspot and coldspot cities are clustered geographically. (4) The spatio–temporal evolution of UPGAs is driven by a complex mechanism, and different factors vary greatly in nature, intensity, spatial effect, and interaction effect. (5) The planning and management of UPGAs in the Grand Canal should be implemented by classifying and zoning, and zoning planning and symbiosis planning should be prepared and implemented based on the results of the analysis. In addition, it is necessary to design differentiated and diversified policies for each planning zone in the future, and to focus on enhancing the synergy of multiple policies in the management, so as to maximize the benefits based on the "combination of policies".

This paper presents innovations in the following areas: (1) It pushes UPGA research to shift from case studies of a single city to systematic studies of regional urban agglomerations. It is a big step forward as a single system is more than the sum of its parts. Against the backdrop of China's urban development entering a new era of regional integration dominated by urban agglomerations, urban belts, urban contiguous areas, and metropolitan areas, the research conclusions of individual cities reached in the past are not entirely applicable to current regional green infrastructure planning, although they have provided good guidance for urban scale green space system planning. (2) By integrating the BCG (Boston Consulting Group) matrix, ESDA (Exploratory Spatial Data Analysis), MLR (Machine Learning Regression), GWR (Geographically Weighted Regression), GeoDetector, and LCRPGR (Ratio of Land Consumption Rate to Population Growth Rate), it comprehensively and systematically reveals the driving mechanisms behind UPGAs while quantitatively evaluating their spatio–temporal evolution patterns and performance, especially analyzing in detail the spatial and interactive effects of different factors. It is a brand-new exploration and discovery. (3) Instead of being limited to or stagnated in the analysis of the change characteristics of UPGAs, this study proposes differentiated zoning planning, integrated symbiotic planning, and multi-policies mix management based on the design of spatial planning and management policies for green areas, parks, and green infrastructure in the Grand Canal of China. It is a remarkable fact that canals are common in all countries of the world, and the technical approach, analytical methods, and results of this paper are not only applicable to China, but can also be used as the basis and reference for canal planning and management in Egypt, India, Indonesia, America, and other countries.

There are still some shortcomings in this study: (1) Due to data and information limitations, this study only took into account the effect of population size in the performance evaluation, while it did not include the heterogeneity of the needs of different populations in the analytical model, which may affect the accuracy of the analysis results. (2) This paper is based on a regional inter-city comparative study with no in-depth analysis of parkland in a single city within the Grand Canal, especially within the key cities, which somewhat constrains the breadth of application of the results. The canal is not only a navigation channel and cultural heritage zone for human beings, but also a natural ecological zone and a source of green well-being for the people living along the route. Beginning with the construction of ecological civilization and ending with the sustainable development of the Grand Canal of China, this study focuses on the regional analysis and planning of UPGAs, expanding the field of canal research from the traditional dimensions of shipping and transportation, water resources, and history and culture to the dimension of green areas. It demonstrates certain theoretical innovations while responding to the practical needs of ecological protection and high-quality development of the Grand Canal.

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

Funding: This research was funded by the Social Science Foundation Project of Hebei Province (HB22YS031).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this paper mainly came from the Ministry of Housing and Urban-Rural Development of the People's Republic of China (https://www.mohurd.gov.cn/index.html, accessed on 12 March 2023), the National Bureau of Statistics (http://www.stats.gov.cn/sj/ndsj/, accessed on 9 February 2023), the Global Change Research Data Publishing & Repository (https://www.geodoi.ac.cn/WebCn/doi.aspx?Id=887, accessed on 13 April 2023), and the Atmospheric Composition Analysis Group of Dalhousie University in Canada (https://www.heywhale.com/mw/dataset/641cfe42a001a17c4784f212, accessed on 18 April 2023).

Acknowledgments: Thank you to Menghan Guo and Mushuang Sun for their assistance in data collection and literature review. All the authors are grateful to the reviewers and editors.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mwanzu, A.; Nguyu, W.; Nato, J.; Mwangi, J. Promoting Sustainable Environments through Urban Green Spaces: Insights from Kenya. *Sustainability* **2023**, *15*, 11873. [CrossRef]
2. Ji, S.W.; Ma, R.F.; Ren, L.Y.; Wang, C.J. How to Find Vacant Green Space in the Process of Urban Park Planning: Case Study in Ningbo (China). *Int. J. Environ. Res. Public Health* **2020**, *17*, 8282. [CrossRef] [PubMed]
3. Evers, M. Integrative River Basin Management: Challenges and Methodologies Within the German Planning System. *Environ. Earth Sci.* **2016**, *75*, 1085. [CrossRef]
4. Eshetu, S.B.; Yeshitela, K.; Sieber, S. Urban Green Space Planning, Policy Implementation, and Challenges: The Case of Addis Ababa. *Sustainability* **2021**, *13*, 11344. [CrossRef]
5. Feltynowski, M. Urban Green Spaces in Land-Use Policy—Types of Data, Sources of Data and Staff—The Case of Poland. *Land Use Policy* **2023**, *127*, 106570. [CrossRef]
6. Buckland, M.; Pojani, D. Green Space Accessibility in Europe: A Comparative Study of Five Major Cities. *Eur. Plan. Stud.* **2022**, *31*, 146–167. [CrossRef]
7. Cernicova-Buca, M.; Gherhes, V.; Obrad, C. Residents' Satisfaction with Green Spaces and Daily Life in Small Urban Settings: Romanian Perspectives. *Land* **2023**, *12*, 689. [CrossRef]
8. Sathyakumar, V.; Raaj, R.; Bardhan, R. Geospatial Approach for Assessing Spatiotemporal Dynamics of Urban Green Space Distribution Among Neighbourhoods: A Demonstration in Mumbai. *Urban For. Urban Green.* **2020**, *48*, 126585. [CrossRef]
9. Chen, C.Y.; Bi, L.L.; Zhu, K.F. Study on Spatial-Temporal Change of Urban Green Space in Yangtze River Economic Belt and Its Driving Mechanism. *Int. J. Environ. Res. Public Health* **2021**, *18*, 12498. [CrossRef]
10. Pinto, L.V.; Inacio, M.; Ferreira, C.S.S.; Ferreira, A.D.; Pereira, P. Ecosystem Services and Well-Being Dimensions Related to Urban Green Spaces-A Systematic Review. *Sustain. Cities Soc.* **2022**, *85*, 104072. [CrossRef]
11. Lee, A.C.K.; Maheswaran, R. The Health Benefits of Urban Green Spaces: A Review of the Evidence. *J. Public Health* **2011**, *33*, 212–222. [CrossRef] [PubMed]
12. Farkas, J.Z.; Hoyk, E.; de Morais, M.B.; Csomos, G. A Systematic Review of Urban Green Space Research over the Last 30 Years: A Bibliometric Analysis. *Heliyon* **2023**, *9*, e13406. [CrossRef] [PubMed]
13. Li, C.Y.; Zhang, T.T.; Wang, X.; Lian, Z.F. Site Selection of Urban Parks Based on Fuzzy-Analytic Hierarchy Process (F-AHP): A Case Study of Nanjing, China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 13159. [CrossRef] [PubMed]
14. Fasihi, H.; Parizadi, T. Analysis of Spatial Equity and Access to Urban Parks in Ilam, Iran. *J. Environ. Manag.* **2020**, *260*, 110122. [CrossRef] [PubMed]
15. Zhang, J.G.; Cheng, Y.Y.; Zhao, B. How To Accurately Identify the Underserved Areas of Peri-Urban Parks? An Integrated Accessibility Indicator. *Ecol. Indic.* **2021**, *122*, 107263. [CrossRef]
16. Senik, B.; Uzun, O. A Process Approach to the Open Green Space System Planning. *Landsc. Ecol. Eng.* **2022**, *18*, 203–219. [CrossRef]
17. Gelo, D.; Turpie, J. Bayesian Analysis of Demand for Urban Green Space: A Contingent Valuation of Developing a New Urban Park. *Land Use Policy* **2021**, *109*, 105623. [CrossRef]
18. Halecki, W.; Stachura, T.; Fudala, W.; Stec, A.; Kubon, S. Assessment and Planning of Green Spaces in Urban Parks: A Review. *Sustain. Cities Soc.* **2023**, *88*, 104280. [CrossRef]
19. Li, Z.; Bai, X.; Xu, Z.J.; Ma, H.Q.; Xu, Y.A.; Wang, N.; Yue, X. The Optimal Spatial Delineation Method for the Service Level of Urban Park Green Space from the Perspective of Opportunity Equity. *Environ. Sci. Pollut. Res.* **2023**, *30*, 85520–85533. [CrossRef]
20. Xu, S.A.; Wang, Y.Z. Influence of Spatial Scale on the Study of Access Fairness of Urban Park Green Space. *Front. Environ. Sci.* **2023**, *10*, 1030796. [CrossRef]
21. Doll, C.A.; Burton, M.P.; Pannell, D.J.; Rollins, C.L. Are Greenspaces Too Green? Landscape Preferences and Water Use in Urban Parks. *Ecol. Econ.* **2023**, *211*, 107896. [CrossRef]
22. Wang, X.K.; Meng, Q.Y.; Liu, X.Z.; Allam, M.; Zhang, L.L.; Hu, X.L.; Bi, Y.X.; Jancso, T. Evaluation of Fairness of Urban Park Green Space Based on an Improved Supply Model of Green Space: A Case Study of Beijing Central City. *Remote Sens.* **2023**, *15*, 244. [CrossRef]
23. Yin, Z.; Zhang, Y.X.; Ma, K.M. Evaluation of PM2.5 Retention Capacity and Structural Optimization of Urban Park Green Spaces in Beijing. *Forests* **2022**, *13*, 415. [CrossRef]
24. Biernacka, M.; Kronenberg, J.; Laszkiewicz, E.; Czembrowski, P.; Parsa, V.A.; Sikorska, D. Beyond Urban Parks: Mapping Informal Green Spaces in an Urban-Peri-Urban Gradient. *Land Use Policy* **2023**, *131*, 106746. [CrossRef]
25. Engstrom, G.; Gren, A. Capturing the Value of Green Space in Urban Parks in A Sustainable Urban Planning and Design Context: Pros and Cons of Hedonic Pricing. *Ecol. Soc.* **2017**, *22*, 21. [CrossRef]
26. Ayele, B.Y.; Megento, T.L.; Habetemariam, K.Y. The Governance and Management of Green Spaces in Addis Ababa, Ethiopia. *Heliyon* **2022**, *8*, e09413. [CrossRef] [PubMed]
27. Molle, F. River-Basin Planning and Management: The Social Life of a Concept. *Geoforum* **2009**, *40*, 484–494. [CrossRef]
28. Antwi, S.H.; Linnane, S.; Getty, D.; Rolston, A. River Basin Management Planning in the Republic of Ireland: Past, Present and the Future. *Water* **2021**, *13*, 2074. [CrossRef]

29. Suhardiman, D.; Bastakoti, R.C.; Karki, E.; Bharati, L. The Politics of River Basin Planning and State Transformation Processes in Nepal. *Geoforum* **2018**, *96*, 70–76. [CrossRef]
30. Safiolea, E.; Baki, S.; Makropoulos, C.; Deliège, J.F.; Magermans, P.; Everbecq, E.; Gkesouli, A.; Stamou, A.; Mimikou, M. Integrated Modelling for River Basin Management Planning. *Proc. Inst. Civ. Eng.-Water Manag.* **2011**, *164*, 405–419. [CrossRef]
31. Merriam, E.R.; Petty, J.T.; Strager, M.P. Watershed Planning within a Quantitative Scenario Analysis Framework. *JOVE-J. Vis. Exp.* **2016**, *113*, e54095. [CrossRef]
32. Matt, J.E.; Underwood, K.L.; Diehl, R.M.; Lawson, K.S.; Worley, L.C.; Rizzo, D.M. Terrain-Derived Measures for Basin Conservation and Restoration Planning. *River Res. Appl.* **2023**, *39*, 1795–1811. [CrossRef]
33. Dutta, S.; Sarkar, S. Canal-Oriented Development: Integrating an Urban Canal Front with the City. *Territ. Ric. Insediamenti Ambiente* **2020**, *13*, 47–65. [CrossRef]
34. Chen, Y. The Hot Spots and Frontiers of Research on the Grand Canal Culture Belt in China: Literature and Academic Trends. *Humanit. Soc. Sci. Commun.* **2022**, *9*, 453. [CrossRef]
35. Yang, J.; Wang, L.; Wei, S. Spatial Variation and Its Local Influencing Factors of Intangible Cultural Heritage Development along the Grand Canal in China. *Int. J. Environ. Res. Public Health* **2023**, *20*, 662. [CrossRef]
36. Li, L. Cultural Communication and Diversity along the Grand Canal of China: A Case Study of Folk Songs in Intangible Cultural Heritage. *Herit. Sci.* **2023**, *11*, 66. [CrossRef]
37. Liu, J.G.; Tan, X.M.; Deng, J.; Zhu, Y.F. Protection and Utilization Strategies for Grand Canal Heritage. In Proceedings of the 35th IAHR World Congress, Chengdu, China, 8–13 September 2013; Volume I–II, pp. 771–779.
38. Cai, J.D.; Peng, J. Introduction of Beijing-Hangzhou Grand Canal and Analysis of Its Heritage Values. In *Water Projects and Technologies in Asia*; CRC Press: Boca Raton, FL, USA, 2019; Volume 26, pp. 2–7. [CrossRef]
39. Li, S.H.; Wang, C.S.; Fu, X.X. Exploring the Cultural Heritage Space Adaptability of the Beijing-Hangzhou Grand Canal Based on Point of Interest Data. *Landsc. Res.* **2023**, *48*, 33–44. [CrossRef]
40. Xu, H. Heritage Landscape Structure Analysis in Surrounding Environment of The Grand Canal Yangzhou Section. In Proceedings of the 3rd International Conference on Energy Equipment Science and Engineering, Beijing, China, 28–31 December 2017; Volume 128, p. 012042. [CrossRef]
41. Zhang, Y.X.; Zhang, C.Y.; Zhang, X.D.; Wang, X.G.; Liu, T.; Li, Z.; Lin, Q.Y.; Jing, Z.H.; Wang, X.Y.; Huang, Q.Y.; et al. Habitat Quality Assessment and Ecological Risks Prediction: An Analysis in the Beijing-Hangzhou Grand Canal (Suzhou Section). *Water* **2022**, *14*, 2602. [CrossRef]
42. Yang, D.Z.; Song, W. Ecological Function Regionalization of the Core Area of the Beijing-Hangzhou Grand Canal Based on the Leading Ecological Function Perspective. *Ecol. Indic.* **2022**, *142*, 109247. [CrossRef]
43. Zhang, Q.; Wang, X.M.; Zhu, J.Q.; Li, Z.; Wang, Y. Occurrence and Risk Assessment of Persistent Organic Pollutants in A Branch of the Grand Canal in Hangzhou, China. *Environ. Monit. Assess.* **2018**, *190*, 211. [CrossRef]
44. Zhou, S.B.; Ye, J.Y.; Li, J.X.; Zhang, G.Q.; Duan, Y.Q. Identifying Intrinsic Drivers to Changes in Riparian Ecosystem Services By Using Psr Framework: A Case Study of the Grand Canal in Jiangsu, China. *Environ. Dev.* **2022**, *43*, 100728. [CrossRef]
45. Lu, L.; Jiao, M.; Weng, L.S. Influence of First-Time Visitors' Perceptions of Destination Image on Perceived Value and Destination Loyalty: A Case Study of Grand Canal Forest Park, Beijing. *Forests* **2023**, *14*, 504. [CrossRef]
46. Zhang, S.Y.; Liu, J.M.; Pei, T.; Chan, C.S.; Gao, C.X.; Meng, B. Perception in Cultural Heritage Tourism: An Analysis of Tourists to the Beijing-Hangzhou Grand Canal, China. *J. Tour. Cult. Chang.* **2023**, *21*, 569–591. [CrossRef]
47. Zhang, S.Y.; Liu, J.M.; Pei, T.; Chan, C.S.; Wang, M.D.; Meng, B. Tourism Value Assessment of Linear Cultural Heritage: The Case of the Beijing-Hangzhou Grand Canal in China. *Curr. Issues Tour.* **2023**, *26*, 47–69. [CrossRef]
48. Zhang, F.; Yang, L.S.; Leo, X. A Study on the Distribution and Utilization of Recreational Resources along the Grand Canal Culture Belt. *Chin. J. Urban Environ. Stud.* **2019**, *7*, 1950015. [CrossRef]
49. He, Y.H.; Wu, L. Analysis on Spatial Development Mode of Eco-Sports Tourism in Grand Canal Landscape Environment Culture Belt. *Environ. Monit. Assess.* **2022**, *194*, 925. [CrossRef] [PubMed]
50. Geng, L.P. The Construction of Public Leisure Space of Beijing-Hangzhou Grand Canal Hangzhou Section. *Adv. Build. Mater. Sustain. Archit.* **2012**, *174–177*, 2289–2292. [CrossRef]
51. Wang, J.Y.; Wang, M.H.; Dou, H.H.; Su, M.M.; Dong, H.Y.; Liu, Z.H. Research on Climate Change and Water Heritage Tourism Based on the Adaptation Theory-A Case Study of the Grand Canal (Beijing Section). *Sustainability* **2023**, *15*, 7630. [CrossRef]
52. Zhang, Y.; Tian, Q.; Wu, J. Coupling Coordination Degree and Obstacle Factors Between the Tourism Industry and Ecological Environment in the Beijing-Hangzhou Grand Canal Basin, China. *Environ. Dev. Sustain.* **2023**. [CrossRef]
53. Chen, M.; Wang, J.C.; Sun, J.; Ye, F.; Zhang, H.Y. Spatio-Temporal Distribution Characteristics of Intangible Cultural Heritage and Tourism Response in the Beijing-Hangzhou Grand Canal Basin in China. *Sustainability* **2023**, *15*, 10348. [CrossRef]
54. Shi, F.; Lu, Y.Y.; Chen, L.G.; Hsu, W.L. Evaluation of the Sustainable Use of Land Resources in the Cities along the Jiangsu Section of the Beijing-Hangzhou Grand Canal. *Land* **2023**, *12*, 1173. [CrossRef]
55. Mukherjee, S.; Shashtri, S.; Singh, C.K.; Srivastava, P.K.; Gupta, M. Effect of Canal on Land Use/Land Cover Using Remote Sensing and GIS. *J. Indian Soc. Remote Sens.* **2009**, *37*, 527–537. [CrossRef]
56. Dale, V.H.; Brown, S.; Calderon, M.O.; Montoya, A.S.; Martinez, R.E. Projected Land-Use Change for the Eastern Panama Canal Watershed and Its Potential Impact. In *The Río Chagres, Panama. A Multidisciplinary Profile of a Tropical Watershed*; Springer: Dordrecht, The Netherlands, 2005; Volume 52, pp. 337–345.

57. Huang, W.J.; Xi, M.W.; Lu, S.B.; Taghizadeh-Hesary, F. Rise and Fall of the Grand Canal in the Ancient Kaifeng City of China: Role of the Grand Canal and Water Supply in Urban and Regional Development. *Water* **2021**, *13*, 1932. [CrossRef]
58. Zhu, C.H.; Nie, Y.P. Study on the Effects of Grand Canal on City Pattern Change of Hangzhou Based on Remote Sensing. In Proceedings of the 2009 Joint Urban Remote Sensing Event, Shanghai, China, 20–22 May 2009; Volume 1–3, pp. 1229–1234.
59. Zhao, Y.; Yan, J.W.; Li, Y.; Bian, G.M.; Du, Y.Z. In-Site Phenotype of the Settlement Space along China's Grand Canal Tianjin Section: GIS-sDNA-Based Model Analysis. *Buildings* **2022**, *12*, 394. [CrossRef]
60. Huo, X.L.; Xu, X.W.; Tang, Y.; Zhang, Z. An Analysis of the Spatial Evolution and Influencing Factors of Rural Settlements along the Shandong Section of the Grand Canal of China. *River Res. Appl.* **2021**, *39*, 1283–1299. [CrossRef]
61. Portela, J.F.; Roda, E.M.M. Rural Development Programs in the Riverside Municipalities of the Canal De Castilla: Their Impact on the Evolution of the Population (2000–2020). *Bol. Asoc. Geogr. Esp.* **2022**, *93*. [CrossRef]
62. Tsung, N.; Corotis, R.; Chinowsky, P.; Amadei, B. A Retrospective Approach to Assessing the Sustainability of the Grand Canal of China. *Struct. Infrastruct. Eng.* **2013**, *9*, 297–316. [CrossRef]
63. Gangopadhyay, A.; Patra, P. The Historical Background of the Canal System in Calcutta, India, and Its Contribution to Development. *Proc. Inst. Civ. Eng.-Eng. Hist. Herit.* **2020**, *173*, 80–91. [CrossRef]
64. Cheng, Z.; He, J.L.; Li, Y.; Zhu, Y.X.; Dai, J.C. Coupling-Coordinated Development of the Water-Economy-Innovation Nexus: A Case Study of the Grand Canal Area in China. *J. Water Resour. Plan. Manag.* **2023**, *149*, 05023016. [CrossRef]
65. Xia, Y.K. Impact of Green Space on Residents' Wellbeing: A Case Study of the Grand Canal (Hangzhou Section). *Front. Public Health* **2023**, *11*, 1146892. [CrossRef]
66. Chen, H.; Zhao, S.; Zhang, P.; Zhou, Y.; Li, K. Dynamics and Driving Mechanism of Real Estate in China's Small Cities: A Case Study of Gansu Province. *Buildings* **2022**, *12*, 1512. [CrossRef]
67. Watson, S.I. Efficient design of geographically-defined clusters with spatial autocorrelation. *J. Appl. Stat.* **2021**, *49*, 3300–3318. [CrossRef] [PubMed]
68. Zhang, P.; Li, W.; Zhao, K.; Zhao, S. Spatial Pattern and Driving Mechanism of Urban–Rural Income Gap in Gansu Province of China. *Land* **2021**, *10*, 1002. [CrossRef]
69. Zhang, P.; Chen, H.; Zhao, K.; Zhao, S.; Li, W. Dynamics, Risk and Management Performance of Urban Real Estate Inventory in Yangtze River Delta. *Buildings* **2022**, *12*, 2140. [CrossRef]
70. Zhao, S.; Zhao, K.; Yan, Y.; Zhu, K.; Guan, C. Spatio-Temporal Evolution Characteristics and Influencing Factors of Urban Service-Industry Land in China. *Land* **2022**, *11*, 13. [CrossRef]
71. Rustamov, J.; Rustamov, Z.; Zaki, N. Green Space Quality Analysis Using Machine Learning Approaches. *Sustainability* **2023**, *15*, 7782. [CrossRef]
72. Yang, Z.Q.; Fang, C.L.; Li, G.D.; Mu, X.F. Integrating Multiple Semantics Data to Assess the Dynamic Change of Urban Green Space in Beijing, China. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *103*, 102479. [CrossRef]
73. Wu, C.; Du, Y.H.; Li, S.; Liu, P.Y.; Ye, X.Y. Does Visual Contact with Green Space Impact Housing Prices? An Integrated Approach of Machine Learning and Hedonic Modeling Based on the Perception of Green Space. *Land Use Policy* **2022**, *115*, 106048. [CrossRef]
74. Walker, K.W.; Jiang, Z.H. Application of adaptive boosting (AdaBoost) in demand-driven acquisition (DDA) prediction: A machine-learning approach. *J. Acad. Libr.* **2019**, *45*, 203–212. [CrossRef]
75. Benocci, R.; Afify, A.; Potenza, A.; Roman, H.E.; Zambon, G. Toward the Definition of a Soundscape Ranking Index (Sri) in an Urban Park Using Machine Learning Techniques. *Sensors* **2023**, *23*, 4797. [CrossRef]
76. Kim, D.; Jin, J. Does Happiness Data Say Urban Parks Are Worth It? *Landsc. Urban Plan.* **2018**, *178*, 1–11. [CrossRef]
77. Zhang, W.J.; Li, J.K. A Quasi-Experimental Analysis on the Causal Effects of Covid-19 on Urban Park Visits: The Role of Park Features and the Surrounding Built Environment. *Urban For. Urban Green.* **2023**, *82*, 127898. [CrossRef] [PubMed]
78. Perez-Martinez, J.; Hernandez-Gil, F.; San Miguel, G.; Ruiz, D.; Arredondo, M.T. Analysing Associations Between Digitalization and the Accomplishment of the Sustainable Development Goals. *Sci. Total Environ.* **2023**, *857*, 159700. [CrossRef] [PubMed]
79. Zhang, P.; Li, W.; Zhao, K.; Zhao, Y.; Chen, H.; Zhao, S. The Impact Factors and Management Policy of Digital Village Development: A Case Study of Gansu Province, China. *Land* **2023**, *12*, 616. [CrossRef]
80. Yang, L.; Li, Y.T. Analysis on the Spatial Differentiation of National Wetland Park and Influencing Factors in Hunan Province. *J. Cent. South Univ. For. Technol.* **2019**, *13*, 99–106. [CrossRef]
81. Li, L.; Zhao, K.; Wang, X.; Zhao, S.; Liu, X.; Li, W. Spatio-Temporal Evolution and Driving Mechanism of Urbanization in Small Cities: Case Study from Guangxi. *Land* **2022**, *11*, 415. [CrossRef]
82. Zhao, S.; Yan, Y.; Han, J. Industrial Land Change in Chinese Silk Road Cities and Its Influence on Environments. *Land* **2021**, *10*, 806. [CrossRef]
83. Dang, Y.; Wang, C.J.; Chen, P.R. Identification and Optimization Strategy of Urban Park Service Areas Based on Accessibility by Public Transport: Beijing as a Case Study. *Sustainability* **2022**, *14*, 7112. [CrossRef]
84. Hasan, M.; Hassan, L.; Al Mamun, A.; Abualreesh, M.H.; Idris, M.H.; Kamal, A.M. Urban Green Space Mediates Spatiotemporal Variation in Land Surface Temperature: A Case Study of an Urbanized City, Bangladesh. *Environ. Sci. Pollut. Res.* **2022**, *29*, 36376–36391. [CrossRef]
85. Mu, B.; Liu, C.; Tian, G.H.; Xu, Y.Q.; Zhang, Y.L.; Mayer, A.L.; Lv, R.; He, R.Z.; Kim, G. Conceptual Planning of Urban-Rural Green Space from a Multidimensional Perspective: A Case Study of Zhengzhou, China. *Sustainability* **2020**, *12*, 2863. [CrossRef]

86. Heshani, A.L.S.; Winijkul, E. Numerical Simulations of the Effects of Green Infrastructure on $PM_{2.5}$ Dispersion in an Urban Park in Bangkok, Thailand. *Heliyon* **2022**, *8*, e10475. [CrossRef] [PubMed]
87. Xing, Z.; Zhao, S.; Li, K. Evolution Pattern and Spatial Mismatch of Urban Greenspace and Its Impact Mechanism: Evidence from Parkland of Hunan Province. *Land* **2023**, *12*, 2071. [CrossRef]
88. You, Z.; Feng, Z.; Yang, Y. Relief Degree of Land Surface Dataset of China (1km). Digital Journal of Global Change Data Repository. *J. Glob. Chang. Data Discov.* **2018**, *2*, 151–155. [CrossRef]
89. Broner, F.; Bustos, P.; Carvalho, V.M. *Sources of Comparative Advantage in Polluting Industries*; NBER Working Paper; National Bureau of Economic Research: Cambridge, MA, USA, 2012; p. 8337. [CrossRef]
90. Hering, L.; Poncet, S. Environmental policy and exports: Evidence from Chinese cities. *J. Environ. Econ. Manag.* **2014**, *68*, 296–318. [CrossRef]
91. Chen, H.; Guo, W.; Feng, X.; Wei, W.; Liu, H.; Feng, Y.; Gong, W. The impact of low-carbon city pilot policy on the total factor productivity of listed enterprises in China. *Resour. Conserv. Recycl.* **2021**, *169*, 105457. [CrossRef]
92. Fortheringham, S.; Brunsdon, C.H.; Charlton, M. *Quantitative Geography*; SAGE Publications: London, UK, 2000.
93. Shrestha, A.; Luo, W. Analysis of Groundwater Nitrate Contamination in the Central Valley: Comparison of the Geodetector Method, Principal Component Analysis and Geographically Weighted Regression. *ISPRS Int. J. Geo-Inf.* **2017**, *6*, 297. [CrossRef]
94. Wang, J.F.; Li, X.H.; Christakos, G.; Liao, Y.L.; Zhang, T.; Gu, X.; Zheng, X.Y. Geographical detectors-based health risk assessment and its application in the neural tube defects study of the Heshun region, China. *Int. J. Geogr. Inf. Sci.* **2010**, *24*, 107–127. [CrossRef]
95. Zhao, S.; Li, W.; Zhao, K.; Zhang, P. Change Characteristics and Multilevel Influencing Factors of Real Estate Inventory—Case Studies from 35 Key Cities in China. *Land* **2021**, *10*, 928. [CrossRef]
96. Wang, J.F.; Hu, Y. Environmental health risk detection with GeogDetector. *Environ. Model. Softw.* **2012**, *33*, 114–115. [CrossRef]
97. Melchiorri, M.; Pesaresi, M.; Florczyk, A.J.; Corbane, C.; Kemper, T. Principles and Applications of the Global Human Settlement Layer as Baseline for the Land Use Efficiency Indicator-SDG 11.3.1. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 96. [CrossRef]
98. Laituri, M.; Davis, D.; Sternlieb, F.; Galvin, K. SDG Indicator 11.3.1 and Secondary Cities: An Analysis and Assessment. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 713. [CrossRef]
99. Rigolon, A. A Complex Landscape of Inequity in Access to Urban Parks: A Literature Review. *Landsc. Urban Plan.* **2016**, *153*, 160–169. [CrossRef]
100. Ren, X.Y.; Guan, C.H. Evaluating Geographic and Social Inequity of Urban Parks in Shanghai Through Mobile Phone-Derived Human Activities. *Urban For. Urban Green.* **2022**, *76*, 127709. [CrossRef]
101. Tan, C.D.; Tang, Y.H.; Wu, X.F. Evaluation of the Equity of Urban Park Green Space Based on Population Data Spatialization: A Case Study of a Central Area of Wuhan, China. *Sensors* **2019**, *19*, 2929. [CrossRef] [PubMed]
102. Gao, W.X.; Lyu, Q.; Fan, X.; Yang, X.C.; Liu, J.T.; Zhang, X.R. Building-Based Analysis of the Spatial Provision of Urban Parks in Shenzhen, China. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1521. [CrossRef]
103. Zhu, J.Y.; Lu, H.T.; Zheng, T.C.; Rong, Y.J.; Wang, C.X.; Zhang, W.; Yan, Y.; Tang, L. Vitality of Urban Parks and Its Influencing Factors from the Perspective of Recreational Service Supply, Demand, and Spatial Links. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1615. [CrossRef] [PubMed]
104. Wu, L.F.; Kim, S.K. Exploring the Equality of Accessing Urban Green Spaces: A Comparative Study of 341 Chinese Cities. *Ecol. Indic.* **2021**, *121*, 107080. [CrossRef]
105. Choumert, J.; Cormier, L. The Provision of Urban Parks: An Empirical Test of Spatial Spillovers in an Urban Area Using Geographic Information Systems. *Ann. Reg. Sci.* **2011**, *47*, 437–450. [CrossRef]
106. Kim, J.; Choi, N.; Lee, D.K. Spatial Preference Heterogeneity in Policies for Improving Urban Green Spaces. *Urban For. Urban Green.* **2022**, *78*, 127781. [CrossRef]
107. Cruickshank, J. Local Hegemonies Resisting a Green Shift and What to Do About It: The Introduction of a Regional Park in Southern Norway. *J. Environ. Policy Plan.* **2018**, *20*, 313–327. [CrossRef]
108. Branca, D.; Haller, A.; Mossa, M. From the mountains to the sea: The Tepilora Natural Regional Park, Sardinia. *eco.mont-J. Prot. Mt. Areas Res. Manag.* **2023**, *15*, 28–34. [CrossRef]
109. Chen, J.X.; Han, S.S.; Chen, S.Q. Understanding the Structure and Complexity of Regional Greenway Governance in China. *Int. Dev. Plan. Rev.* **2022**, *44*, 241–264. [CrossRef]
110. Cheng, Y.; Shi, Y.; Andrew, S. Exploring the Link Between Fiscal Arrangements and the Quality of Public Services: Evidence from Major Us Urban Park Systems. *Public Perform. Manag. Rev.* **2020**, *43*, 1445–1470. [CrossRef]
111. Nam, J.; Dempsey, N. Place-Keeping for Health? Charting the Challenges for Urban Park Management in Practice. *Sustainability* **2019**, *11*, 4383. [CrossRef]
112. Smith, A.; Whitten, M.; Ernwein, M. De-municipalisation? Legacies of Austerity for England's Urban Parks. *Geogr. J.* **2023**. [CrossRef]
113. Luo, T.; Yang, F.M.; Wu, L.L.; Gao, X.H. Equity Evaluation of Urban Park System: A Case Study of Xiamen, China. *J. Environ. Eng. Landsc. Manag.* **2020**, *28*, 125–136. [CrossRef]
114. Feng, S.; Chen, L.D.; Sun, R.H.; Feng, Z.Q.; Li, J.R.; Khan, M.S.; Jing, Y.C. The Distribution and Accessibility of Urban Parks in Beijing, China: Implications of Social Equity. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4894. [CrossRef]
115. Kim, K.; Lee, C.K.; Kim, H.W. Understanding the Accessibility of Urban Parks and Connectivity of Green Spaces in Single-Person Household Distribution: Case Study of Incheon, South Korea. *Land* **2022**, *11*, 1441. [CrossRef]

116. Guo, S.H.; Song, C.; Pei, T.; Liu, Y.X.; Ma, T.; Du, Y.Y.; Chen, J.; Fan, Z.D.; Tang, X.L.; Peng, Y.; et al. Accessibility to Urban Parks for Elderly Residents: Perspectives from Mobile Phone Data. *Landsc. Urban Plan.* **2019**, *191*, 103642. [CrossRef]
117. Guo, S.H.; Yang, G.G.; Pei, T.; Ma, T.; Song, C.; Shu, H.; Du, Y.Y.; Zhou, C.H. Analysis of Factors Affecting Urban Park Service Area in Beijing: Perspectives from Multi-Source Geographic Data. *Landsc. Urban Plan.* **2019**, *181*, 103–117. [CrossRef]

land

Article

Assessing Spatial Heterogeneity in Urban Park Vitality for a Sustainable Built Environment: A Case Study of Changsha

Liwei Qin [1,†], Wenke Zong [1,†], Kai Peng [1] and Rongpeng Zhang [1,2,3,*]

[1] School of Architecture and Planning, Hunan University, Changsha 410082, China; qinliweihaha@hnu.edu.cn (L.Q.); zwkkk@hnu.edu.cn (W.Z.); pengkai@hnu.edu.cn (K.P.)
[2] Hunan Key Laboratory of Sciences of Urban and Rural Human Settlements in Hilly Areas, Hunan University, Changsha 410082, China
[3] Hunan International Innovation Cooperation Base on Science and Technology of Local Architecture, Changsha 410082, China
* Correspondence: zhangrongpeng@hnu.edu.cn
† These authors contributed equally to this work.

Abstract: In the realm of sustainable city development, evaluating the spatial vitality of urban green spaces (UGS) has become increasingly pivotal for assessing public space quality. This study delves into the spatial heterogeneity of park vitality across diverse urban landscapes at a city scale, addressing limitations inherent in conventional approaches to understanding the dynamics of park vitality. Leveraging geotagged check-in data from 65 parks in the study case of Changsha City, a quantitative analysis was undertaken to assess spatial vitality. The investigation incorporated data concerning internal and external factors influencing park vitality, employing the Multi-scale Geographically Weighted Regression (MGWR) model to dissect nuanced spatial heterogeneity. The research uncovers notable spatial discrepancies in factors influencing park vitality across diverse urban areas, emphasizing the reliance on adjacent residential communities and internal commercial amenities provision. These dependencies correspond with economic development differences among urban locales, revealing distinct geographic trends. This study has a novel perspective and methodology for investigating urban park vitality, providing significant insights for urban green space planning and management. It emphasizes the necessity of acknowledging spatial diversity in urban park planning and design by incorporating the distinct socio-economic characteristics of each urban zone, which is crucial for both urban planners and policymakers.

Keywords: urban parks vitality; spatial heterogeneity; MGWR; public space quality; urban livability

Citation: Qin, L.; Zong, W.; Peng, K.; Zhang, R. Assessing Spatial Heterogeneity in Urban Park Vitality for a Sustainable Built Environment: A Case Study of Changsha. *Land* **2024**, *13*, 480. https://doi.org/10.3390/land13040480

Academic Editors: Luca Battisti, Fabrizio Aimar and Federico Cuomo

Received: 1 February 2024
Revised: 31 March 2024
Accepted: 4 April 2024
Published: 8 April 2024

1. Introduction

Globally, including in China (the most populous developing nation), urbanization rates have significantly increased, soaring from 30% in 1996 to 65% in 2022, presenting challenges such as unequal resource distribution and unplanned urban expansion [1–3]. Urban parks, as a crucial component of the urban ecosystem, play an indispensable role in mitigating urban challenges such as the heat island effect, environmental quality degradation, and increased stress among urban residents resulting from intense urbanization. Furthermore, urban parks offer spaces for leisure, entertainment, and social interaction, acting as a vital catalyst for community revitalization and urban development [4–7].

Currently, scholars focus not only on the quantity of Urban Green Spaces (UGS) within cities, but also on the impact of UGS on surrounding residents post-construction. The influence of different urban parks on the urban environment varies, as does their frequency of use as public infrastructure. To accurately describe this impact, various indicators have been employed by different scholars. Notably, the concept of urban spatial vitality proposed by Montgomery and Jacobs has received widespread recognition within the academic community. This concept characterizes the vitality of urban spaces as activities related to the number of people within and around streets or communities [8,9].

In UGS vitality research, accurately assessing vitality is challenging due to varying analytical scales, datasets, and methodologies [6,10,11]. Traditional quantitative models such as questionnaire surveys, field observations, and drone surveys [12–14] provide authentic data, but are limited by time, resources, and potential biases [15]. Information technology and increased smartphone usage have enabled social platforms' open API interfaces (e.g., Twitter, Weibo, Dazhong Dianping) to extract geospatial data for understanding spatial preferences and urban vitality [16–19]. This data is abundant, extensive, and easily accessible, proving useful in urban studies across cities like Birmingham [20] and Oslo [21]. Heatmaps and mobile phone signaling data also contribute to spatial vitality research [22–24]. However, global models, while providing macro-level insights, may not capture spatial heterogeneity as highlighted by the Second Law of Geography [25,26], leading to potential discrepancies when applied to specific local contexts [27].

With the deepening research on urban spatial vitality, an increasing number of scholars are focusing on the causes of the differences in the vitality of UGS. Against this backdrop, scholars in the fields of geography and urban planning generally believe that spatial heterogeneity is a key concept in explaining this phenomenon [28]. It delineates the variance and disparity in spatial attribute values across diverse geographical locales. This heterogeneity mirrors the impact of factors such as the natural environment, socioeconomic conditions, and human endeavors on the spatial layout, serving as a fundamental theory for comprehending and examining geographical phenomena [29–31].

In the face of such complex and diverse spatial variations, accurately identifying key factors is a prerequisite for enhancing the vitality of UGS. The Geographically Weighted Regression (GWR) model, a local regression analysis approach, performs local regressions on all independent variables within the same bandwidth to unearth the spatial relationships between independent and dependent variables. This model has found extensive applications in disciplines such as geography and economics [32,33]. Research shows that, compared to the global model, the GWR model has a higher fitting degree [34–36]. However, UGS vitality is influenced by a complex mix of factors like population, economy, environment, and transportation, which exhibit spatial heterogeneity and vary across scales [22,37,38]. Therefore, an analytical method that effectively addresses spatial heterogeneity and scale effects is essential for accurately assessing park vitality [23]

Fotheringham's introduction of the Multiscale Geographical Weighted Regression (MGWR) has provided a leap forward in spatial heterogeneity analysis by overcoming the fixed bandwidth constraint of the traditional GWR [24], permitting an individual bandwidth application for each variable. This advancement enhances the accuracy of such analysis, substantiated by numerous studies demonstrating the MGWR model's superior fitting, precision, and practicality relative to the GWR model [39–41]. Amidst dynamic shifts in urban landscapes and the behavioral patterns of residents, the integration of urban parks' dynamic nature and MGWR's capabilities allows tailored updating strategies to be formulated based on the spatial heterogeneity of different space vitality influencers. This method transcends the traditional approach of relying on global model "averages" to develop a strategy. It optimizes the GWR model's fitness, grounding the research in reality and thus amplifying the experimental authenticity. Furthermore, this more profound insight into the urban park's operational principles aids in reducing both the temporal and technical costs associated with urban park updates.

Extant scholarly discourse on UGS vitality has achieved a commendable degree of maturity. Yet, many of these studies still need to tackle the spatial variations in the impact of different determinants on UGS vitality, suggesting an opportunity for more comprehensive and rigorous investigation. The study aims to explore the spatial vitality of UGS in Changsha City, employing the MGWR model alongside multi-source, voluminous datasets, including Baidu Huiyan vitality data and Amap geospatial information. By assessing the spatial heterogeneity of influencing factors, the research seeks to enhance the precision of evaluating UGS vitality and inform tailored strategies for urban park planning. Using Changsha as a case study, this research offers a novel approach to examining urban park vitality. It facilitates a deeper understanding of the global patterns and regional disparities in the vitality of urban green spaces, thereby providing valuable insights for other international cities.

The remainder of this paper proceeds in the following way. Section 2 offers a comprehensive review of vitality and spatial heterogeneity studies. Section 3 delineates the study area and delineates the data sources utilized in this research, and further expounds on the analytical framework and procedural methodology employed in the investigation. Section 4 presents the findings from the ordinary least squares (OLS), GWR, and MGWR analyses. Section 5 delves into a discussion of the outcomes and underlying reasons for spatial heterogeneity. Section 6 encapsulates the critical discoveries of the study and proposes avenues for future research endeavors.

2. Literature Review

2.1. Space Vitality

Urban vitality is a pivotal concept, intricately linked to the intensity of activities within public spaces, particularly at the street and community levels [42]. Jacobs conceptualizes urban vitality as the continuity and diversity of street life over 24 h [9]. Conversely, Montgomery characterizes urban vitality as the volume of pedestrian traffic in streets or communities and their adjacent areas across different time intervals [43]. This notion underscores the dynamic and interactive nature of public spaces, mirroring the activities and interactions of individuals within urban settings. Urban vitality extends beyond mere population movements and gatherings; it encompasses various economic, cultural, and social dimensions. It is a crucial metric for assessing the quality of urban life and the capacity for sustainable development. Researchers delineate vitality through diverse factors such as heatmap data [44], mobile signaling data [44], nighttime light data [45], and online check-in data [42,46].

One of the defining characteristics of urban spatial vitality is the population fluctuation within a space due to variables such as time and weather [47]. Location-based services (LBS) data hold distinct advantages over traditional social check-in or survey data: firstly, social check-in data fail to capture the dynamic population changes within a space over time, whereas LBS data can accurately depict the population flow within a space during different periods; secondly, check-in data only represent the habits of a subset of the population, and cannot account for all participants in a space. In the era of information, LBS data can encompass a broader range of individuals, thereby providing a more authentic reflection of the number of people in a space.

In this research, we utilize heat data from Baidu Huiyan as the data source for park vitality analysis. Baidu Huiyan leverages big data technology to collect and analyze users' location information and search behavior on Baidu Maps, producing heat maps that depict the density of people and the intensity of activities. This operational principle enables Baidu Huiyan to capture the dynamic changes of heat thoroughly, offering a wealth of representative and timely data. Its feasibility has been demonstrated in various fields [48,49]. For the study of the spatial heterogeneity of park vitality, Baidu Huiyan's heat map data can unveil the spatial distribution characteristics of vitality across different regions, providing a scientific foundation for a deeper comprehension of park vitality.

2.2. Spatial Heterogeneity

Spatial heterogeneity is a fundamental concept in geography, urban planning, and related disciplines, characterized by the uneven distribution and variability of attributes, characteristics, or phenomena across diverse geographic locations or spatial scales [28]. This concept plays an integral role in understanding the complexity inherent in spatial patterns and processes, acknowledging that distinct regions may display unique attributes due to environmental conditions, socio-economic dynamics, and human interventions. The significance of spatial heterogeneity lies in its capacity to enhance the understanding of spatial relationships and interactions, challenging the presumption of spatial homogeneity, which can result in overly simplified models and inaccurate depictions of reality [50]. By embracing spatial heterogeneity, researchers and planners are empowered to develop more accurate and contextually relevant analyses, models, and strategies.

Spatial heterogeneity has gained widespread application in the domain of spatial relationship analysis, including in areas such as urban public health [51], housing prices and the built environment [52], social equity [53], and soil environmental analysis [54]. In the context of urban vitality analysis, research typically centers on urban landscapes, streets, or morphologies [55,56]. However, previous studies have often neglected a crucial aspect: the vitality of parks as urban public spaces, along with their influencing factors, can display spatial heterogeneity in response to changes in the surrounding economy, activities, and population structure [38,57]. More research is needed on the spatial heterogeneity of urban park vitality. While traditional analysis methods (such as global regression, surveys, and interviews) can provide detailed analyses of the vitality and its influencing factors for parks across an entire city, these results may not be suitable for specific parks. They cannot be extrapolated to a broader context.

2.3. Factors Affecting UGS Spatial Vitality

Investigating the influence of internal or external factors on park vitality is a research domain that has been explored previously. Scholars across various regions have introduced diverse analytical perspectives on park vitality in their respective study areas, considering the disparities in national customs, economic development levels, urbanization processes, and population structures. For instance, research has been conducted in Poland [58], Berlin and Salzburg [59], and Melbourne, Australia [12]. The surrounding population and economic activities significantly influence the vitality of parks; for example, parks equipped with playgrounds are favored by children [60], while serene environments are preferred by older people [12]. Moreover, factors such as accessibility, economic environment, and residential and office areas, all contribute to park vitality [61–63]. Nonetheless, there are variations in the factors affecting park vitality between different cities and even among parks within the same city. Regrettably, the spatial heterogeneity analysis of park vitality and its influencing factors remains insufficient.

Since adopting the reform and opening-up policy in 1978, China has witnessed a substantial rise in urbanization rates and a rapid expansion of urban permanent populations. Accompanying large-scale population movements, cities' economic stratification and spatial distribution differences have become increasingly pronounced, particularly in major cities such as Beijing and Shanghai [64,65]. These transformations have resulted in variations in the surrounding environment, population structure, and economic activities of urban parks. In contrast to Western cities, the swift development of Chinese cities has attracted a considerable influx of migrant workers, amplifying park vitality's spatial heterogeneity [66]. Research indicates that distinct age and gender groups exhibit differing demands for parks [12,60]. Consequently, considering the alterations in population structure and spatial distribution, analyzing UGS vitality and its influencing factors from a spatial heterogeneity perspective, and devising corresponding renewal strategies are imperative for enhancing the vitality of UGS.

Research on the spatial heterogeneity of park vitality conducted in China offers distinctive insights for the global academic community. The swift urbanization and population mobility patterns in China starkly contrast with the racial geographical segregation in the United States [67], immigration issues in Europe [68], and urban expansion in Australia [69], thereby unveiling the diversity of park vitality across different socio-economic contexts. In Chinese cities, the spatial heterogeneity of park vitality is predominantly influenced by internal population structures and economic activities. In contrast, in American and European cities, park vitality is significantly shaped by racial and immigration factors. By examining these varied influencing factors, researchers can attain a more holistic understanding of the intricacies of park vitality and devise targeted park planning and management strategies for cities worldwide. Thus, research on park vitality in China guides domestic urban planning and offers valuable insights for tackling similar challenges internationally.

3. Methodology

3.1. Study Area

Changsha, the capital city of the Hunan Province in China, administers six districts (Furong, Tianxin, Yuelu, Kaifu, Yuhua, Wangcheng) and one county (Changsha County), encompassing a total population of 10 million across 11,819 km^2 as of the close of 2022 (Changsha Statistical Yearbook). As the vibrant political, economic, and cultural hub of Hunan Province, Changsha has drawn a substantial migratory population for work and residence. However, juxtaposed with the population influx and the swift urban development, the urban park construction area expanded only modestly, from 575 km^2 in 2001 to 2797 km^2 by 2020. Considering the lower population density on the city's periphery, and the predominance of large forest parks resulting in lesser spatial utilization, this study primarily focuses on the principal urban area of Changsha, precisely within the perimeters of the Changsha Ring Expressway.

The delineated study area encompasses a total of 152 UGS. However, the scope of this research does not extend to diminutive community parks, given their relatively limited expanse and influence when juxtaposed with the city's comprehensive spatial domain. These smaller entities exhibit negligible spatial heterogeneity within their constrained service radius, rendering them incongruent with the study's foundational aim to scrutinize urban parks that cater to the populace across more expansive vicinities. Consequently, this investigation excludes small-scale pocket parks and community parks. In stark contrast, municipal parks, characterized by their extensive service range, heightened user participation, and a myriad of influencing factors present a more compelling case for analyzing spatial heterogeneity in factors affecting UGS vitality. In alignment with the stipulations of the "Standard for the Planning of Urban Green Space (GB/T51346-2019)", this study meticulously selects 65 parks from the study region as the focal point of its analytical endeavors.

This study is focused on the main urban area within the Changsha Ring Expressway (Figure 1), guided by the following academic considerations: Firstly, this region is characterized by a high concentration of economic activities and population density, highlighting the significance of parks in the daily lives of urban residents. Furthermore, the abundance and diversity of park resources in this area provide a comprehensive data foundation for examining the spatial heterogeneity of park vitality. Ultimately, by concentrating on the urban core, this research aims to enhance the precision and practical value of the study, deepening the understanding of the characteristics and influencing factors of urban park vitality, thereby contributing specific and targeted insights to the formulation of relevant policies and renewal strategies.

3.2. Study Framework

Figure 2 illustrates the spatial heterogeneity assessment framework and procedures for UGS vitality and its influencing factors. The assessment framework includes three steps, as detailed below.

In step1, the process involves acquiring spatial location data pertinent to UGS vitality and its influencing factors within the urban confines of Changsha City. At this juncture, it is imperative to identify the specific nature and category of data pertinent to UGS vitality and the contributory elements that should be encompassed within the dataset. Given the necessity for an extensive dataset, the utilization of publicly accessible API interfaces is employed to facilitate the aggregation of large-scale data. The harvested data must undergo meticulous cleansing and calibration to maintain the experimental integrity. A comprehensive outline of these procedural steps will be delineated in Section 2.2.

In step2, an Ordinary Least Squares (OLS) regression is employed to conduct a global analysis of UGS vitality in conjunction with selected spatial vitality determinants. This approach is primarily adopted to circumvent the potential multicollinearity issues among the influencing factors, which could compromise the integrity of subsequent spatial heterogeneity analyses. Concurrently, this step facilitates a comprehensive understanding of the overarching analytical context.

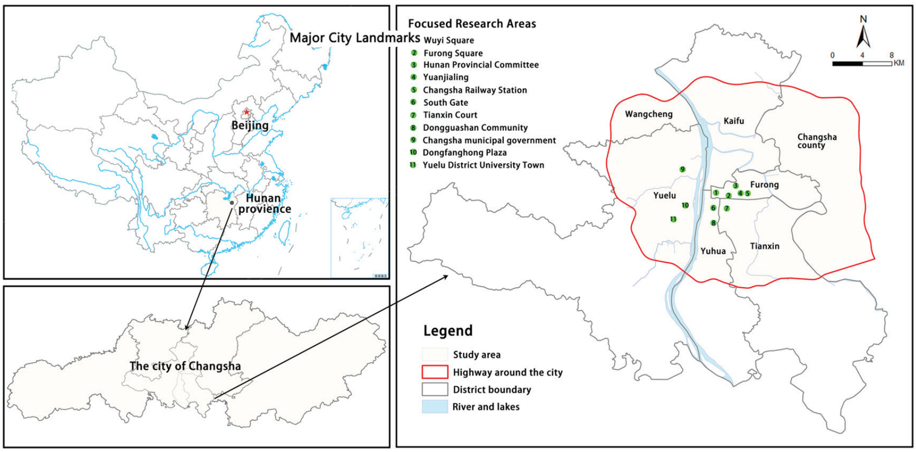

Figure 1. Changsha City: location and research scope.

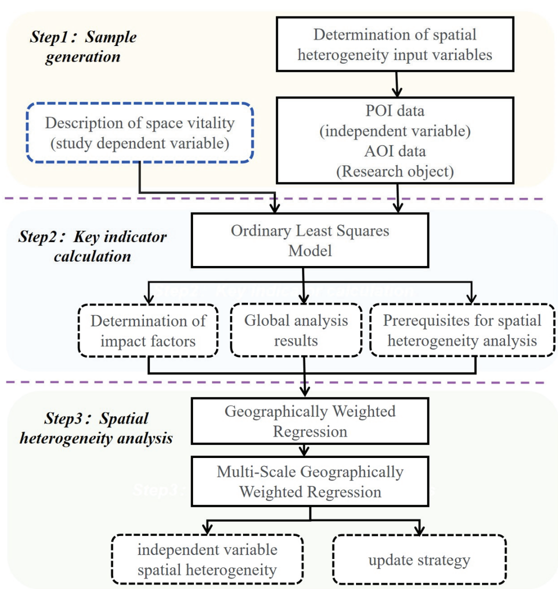

Figure 2. Framework of the spatial heterogeneity assessment.

In step3, the influencing factors, having been rectified for multicollinearity through the application of OLS, are subsequently processed through GWR and MGWR models, respectively. This process involves a comparative reliability analysis of the experimental data outcomes derived from both models, thereby elucidating the spatial heterogeneity of factors influencing park vitality in Changsha City. The empirical findings are then leveraged to inform targeted refinement strategies for UGS in subsequent interventions.

3.3. Data Resources

3.3.1. AOI and POI Data

This research initially necessitates the acquisition of fundamental spatial data about UGS within the study locale. Consequently, this article employs AOI and POI datasets to depict the UGS and its adjacent amenities, and amalgamates them for subsequent analysis via a Geographic Information System (GIS) platform. AOI data, a prevalent form of spatial data in digital cartography, encompasses essential attributes like name, address, category, and geographical coordinates. It also includes boundary coordinate information, rendering it a comprehensive tool for depicting two-dimensional geographic entities on maps. Like AOI data, POI data provides essential information, including name, address, category, and coordinates. It is known for its substantial volume, extensive coverage, precision, and ease of acquisition [70]. Therefore, the utilization of AOI and POI data within the GIS platform effectively delineates the spatial information of urban UGS and its adjacent facilities, thereby offering crucial data support for conducting spatial analysis of urban UGS resources.

Acquiring AOI and AOI data is primarily facilitated through various navigation platforms, including but not limited to Baidu Maps, Amap, and Google Maps [10,15,20]. For this study, AOI and POI data about UGS was meticulously sourced via the open API interface of Amap (https://lbs.amap.com/, accessed on 1 October 2023). As China's leading electronic map, navigation, and Location-Based Services (LBS) platform, Amap boasts an average daily active user count exceeding 100 million. This substantial user base reflects the platform's extensive reach and utility and corroborates the high quality of its sample data. This feature has garnered widespread recognition and endorsement within the academic community (Figure 3).

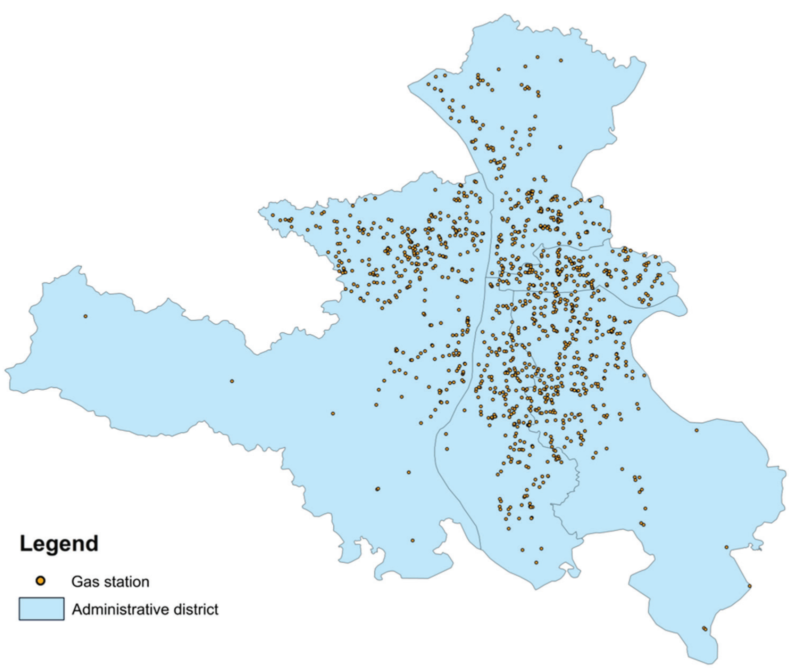

Figure 3. POI and AOI data examples: gas stations' POI data and administrative division AOI data at five districts in Changsha.

3.3.2. UGS Vitality Data Source

In the wake of the relentless advancements in information technology, Baidu, a titan in China's internet industry, holds numerous apps and the geospatial big data platform Baidu Huiyan under its aegis. Baidu Huiyan registers an astounding average of 120 billion location requests daily, supporting 1.1 billion active hardware devices monthly. Many scholars have harnessed the potential of the Baidu Huiyan platform, conducting diverse analyses across several cities in China and establishing the precision and effectiveness of the platform's data. This study also taps into the city population geographic big data platform of Baidu Huiyan (https://huiyan.baidu.com, accessed on 10 October 2023) to extract real-time population distribution data for Changsha City for 2022. This data is a derivative of the statistics collated from terminal positioning data that invokes the Baidu Map Location SDK. Initially, Baidu Map sections the entire nation into 200 $\times$ 200 m grids based on the Baidu Mercator coordinate system (bdmc09), tallying the number of terminals that engaged the location SDK over a particular time frame (defaulted to one hour on the platform). Importantly, all stages of data handling have been anonymized, ensuring individuals' privacy is not compromised (Figure 4).

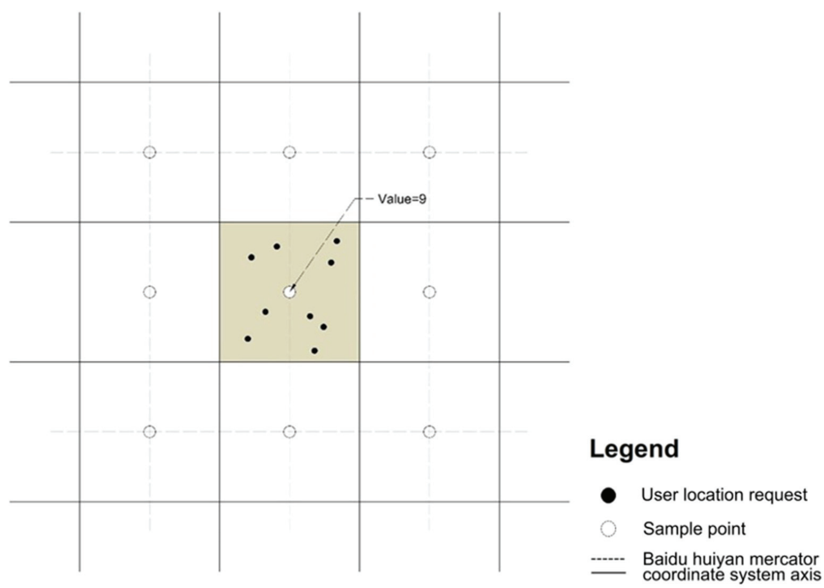

Figure 4. Baidu Huiyan vitality data crawling principle.

3.3.3. Descriptive Statistics of Key Variables

As shown in Table 1, upon contemplating the independent variables that bear upon the UGS vitality, we categorize them into three groups: (1) external factors, (2) internal factors, and (3) landscape factors. External factors primarily pertain to the facilities around the park, which are capable of ushering in a primary pedestrian flux, such as residential areas, commercial facilities, subway stations, bus stops, and public service amenities. Because the principal users of various urban parks hail from the active population or permanent residents in a specific periphery, previous studies have unveiled a potent correlation between economic-commercial activities and the intensity of population activities [71–73]. Concurrently, it has been discovered that commercial facilities and public service amenities can significantly influence the vitality of urban parks [74,75]. The ongoing advancement in urban transportation has underscored the significance of accessibility as a pivotal determinant of UGS vitality. This rationale has led to including urban public transportation facilities, specifically subway stations and bus stops, as independent variables in our research. [76].

Another significant user demographic for UGS involves the permanent residents in the surrounding areas, hence their inclusion in our scope of consideration.

Table 1. Reasons for selecting independent variables and crawling keywords.

POI Type	Description	Crawl Keywords
	Internal facilities	
Open space	Provide activity needs and social space for different groups of people	Natural scenery, squares, scenic spots, observation decks, etc.
Sport facilities	Increase space usage and attract sports-loving people	Sports facilities
Entrance/Exit	Reflection of park accessibility and connection to surrounding communities	Door, entrance, exit
Public toilet	Provide parks with comfort and hygiene levels to attract people	Toilet
Business	Meet the consumption needs and diverse needs of visitors	Companies, wholesale markets, snacks, catering, restaurants, etc.
	External facilities	
Residential communities	Provide a stable source of visitors to the park	Residential areas, dormitories, communities, real estate
Transportation facilities	Providing parks accessibility	Subway, parking lot, bus station
Eateries	Extend visitor stay time and increase visitor social activities	Snacks, catering, restaurants
Companies	Increase daily users and the diversity of park uses	Companies, offices, etc.
Public infrastructure	Increase the number of visitors and promote interactive communication	Art galleries, museums, cultural centers, planetariums, etc.

Internal factors encompass: park entrance, open space (like scenic spots, squares and viewpoints), sports facilities, public toilets and business. The selection of variables impacting the internal UGS vitality is based on the distinctive participation priorities of various demographic groups in park spaces and the variable spatial vitality generated by different facilities within the park. Studies have revealed that sports amenities, such as sandpits and open fitness facilities, often lure a younger audience, thus contributing to significant spatial vitality [77,78]. On the other hand, open spaces conducive to socialization, leisure areas, and commercial zones also foster spatial vitality concentration [74,79,80].

The selection of the search radius for retrieving POI data significantly impacts the accuracy of spatial heterogeneity analysis. Both larger and smaller search ranges may result in discrepancies with real-world situations and potentially compromise the fidelity of overall distribution. Drawing upon insights from previous research, this study conducted multiple experiments to determine the optimal search radius values [81–83]. This ensures that the analysis results retain greater detail and effectively portray the spatial distribution characteristics of spatial heterogeneity. The search range of each influencing factor is shown in Table 2.

Table 2. Description of the POI's search radius.

	POI Type	Number	Search Radius
Internal facilities	Open space	413	Internal of UGS
	Sport facilities	60	Internal of UGS
	Entrance/Exit	200	Internal of UGS
	Public toilet	169	Internal of UGS
	Business	257	Internal of UGS
External facilities	Residential communities	10,779	600 m
	Transportation facilities	525	400 m
	Eateries	7125	300 m
	Companies	3588	600 m
	Public infrastructure	111	600 m

Landscape elements relate to the motivations that drive citizens to visit parks. Generally, a park is designed around a single theme, but preferences for landscape types vary across different age groups. For instance, studies have indicated that the needs of older adults [12,81] and adolescents [82] for park spaces and landscape elements [59] are distinct.

Environments that inspire a sense of safety all influence spatial vitality [14]. Typically, urban parks are themed around water or forest sceneries, or a combination of various themes. However, it is not feasible to directly compare riverside, lakeside, or vegetation landscapes or quantify multiple coexisting thematic landscape elements. Thus, this study disregards landscape factors and concentrates on quantifiable internal and external factors when analyzing UGS vitality.

3.4. Analysis Model

3.4.1. Global Analysis Model

A stepwise regression technique has been employed to address the issue of multicollinearity among the variables. This involves systematically introducing variables; each time a new variable is added, an evaluation of each of the variables already incorporated into the regression model is conducted, and those deemed insignificant are removed. This ensures that every variable within the resulting subset of independent variables carries significance. This procedure is repeated in numerous steps until no further variables can be incorporated. By this stage, all variables within the regression model hold significant relevance to the dependent variable while minimizing the collinearity among factors. The Ordinary Least Squares (OLS) model is a global regression model, the results are displayed as panel data, representing mathematical significance only and excluding the geographic spatial attributes of the explanatory and dependent variables. The corresponding formula is as follows:

$$y(i) = \hat{\beta}_0(i) + \hat{\beta}_1 X_1(i) + \hat{\beta}_2 X_2(i) + \ldots + \hat{\beta}_k X_k(i) + \varepsilon(i) \tag{1}$$

In this model, $y(i)$ represents the observed value of the dependent variable at the i^{th} position, $\hat{\beta}_0$ is the estimated intercept, $X_k(i)$ denotes the observed value of the k^{th} explanatory variable at the i^{th} position, $\hat{\beta}_k$ is the estimated value of the k^{th} parameter, and $\varepsilon(i)$ is the random error term, with $i = \{1, 2, 3, \ldots, n\}$. The OLS model posits that all variables are spatially constant. Nonetheless, the same variable may not reflect the same influence due to geographical disparities or environmental variations. Under such circumstances, the "average value" of all variables, as depicted by the OLS results, may not apply to specific regions.

3.4.2. Spatial Heterogeneity Analysis Model

Compared to the OLS model, the GWR approach considers the spatial heterogeneity of variables and presupposes non-smooth spatial fluctuations. At its core, GWR captures spatial variations by calibrating a multivariate regression model consisting of a set of local linear models at any number of positions. It allows for different geographic relationships and "borrowing" data from nearby locations [50,51]. The equation is as follows:

$$y_i = \beta_0(u_i, v_i) + \sum\nolimits_k \beta_k(u_i, v_i) X_{ik} + \epsilon_i \tag{2}$$

In the equation, (u_i, v_i) are the specified coordinates of observation point i in space; β_0 represents the intercept value at location i; β_k is the local coefficient for each k explanatory variable X_{ik} at location i, and ϵ_i is the random error at that location. As a local regression model, GWR results heavily depend on selecting criteria for goodness-of-fit. The Akaike Information Criterion (AIC), renowned for its high level of fit, has been chosen for this study. The bi-square kernel function is employed to select data borrowing and bandwidth. The reasoning is twofold: firstly, the nearest neighbor definition of proximity is more stable for irregular spatial sampling; secondly, the interpretation of the bi-square kernel function is that the bandwidth is the number of nearest neighbors, and any data beyond the bandwidth has zero impact on the observation point [23]. Minimizing the corrected Akaike Information Criterion (AICc) allows us to select the optimal bandwidth parameter, which balances model variance and bias [50].

When examining the factors that influence the spatial vitality of urban parks, GWR applies a uniform bandwidth to multiple variables for search computations. However, different influencing factors and activities pertain to different spatial scales. The MGWR improves upon GWR by allowing varying bandwidths to study relationships instead of the same bandwidth across the entire research area. This approach allows for better capture of independent variables' spatial heterogeneity and reduces parameter estimation errors [38]. The formula is as follows:

$$yi = \sum_{j=1}^{k} \beta_{bwj}(u_i, v_i)x_{ij} + \epsilon_i \tag{3}$$

where bwj signifies the bandwidth of the jth variable estimated using the bi-square kernel function, $\beta_{bwj}(u_i, v_i)$ stands for the MGWR estimate at the location (u_i, v_i), and ϵ_i is the random error term. MGWR calibrates via a back-fitting algorithm, with the bandwidth selection criterion being the Akaike information criterion, which is consistent with GWR. As suggested by Yu et al., the bi-square kernel function is chosen as the optimal bandwidth for independent variables in MGWR, given the usage of the GWR model as the basis [84].

The back-fitting algorithm is typically utilized to calibrate generalized weighted models, assuming that all other terms are known and calibrating each term in the model more smoothly [24]. The convergence criterion for the MGWR back-fitting algorithm is the residual sum of squares (RSS). The formula follows:

$$SOC_{RSS} = \left| \frac{RSS_{new} - RSS_{old}}{RSS_{new}} \right| \tag{4}$$

where SOC_{RSS} is the convergence criterion, RSS_{new} represents the residual sum of squares calculated from the previous step, and RSS_{old} stands for the residual sum of squares calculated for the next step.

4. Results

4.1. UGS Vitality Analysis

In this study, the measurement of urban park vitality is predicated upon in-park check-in data. Specifically, three representative time points for check-ins were selected, and the data from these time points were superimposed to indicate the park's vitality for that day. This approach accounts for the utilization of the park during different periods, and can more comprehensively reflect the level of activity within the park. Furthermore, to obtain a more stable and reliable measurement of park vitality, the data were aggregated over seven consecutive days to yield a weekly measure of park vitality. This method of continuous superposition mitigates daily fluctuations. It captures the trend of park vitality over time, providing adequate data support for analyzing the spatial heterogeneity of urban park vitality.

Considering the climatic conditions of Changsha City, this study identified three pivotal time points (9 a.m., 1 p.m., and 7 p.m.). By employing superposition analysis on these temporal datasets, the fundamental vitality distribution of parks in Changsha City was computed (Figure 5).

The findings of this investigation elucidate pronounced spatial heterogeneity in the vitality of urban parks within Changsha City. Specifically, parks west of the Xiangjiang River near commercial and residential developments manifest heightened vitality levels. Moreover, the University Town precinct, notably West Lake Park, a hub of dense student population, demonstrates robust vitality. Comparatively, parks in the northwest region exhibit notably diminished vitality compared to their counterparts in the southern region west of the Xiangjiang River. This disparity is primarily attributable to the predominant presence of industrial parks in the northwest and its relatively later stage of development.

Further analysis indicates that the vitality of park spaces in the eastern Xiangjiang area could be much higher. Moreover, as the developmental focus of Changsha City is primarily directed towards the area west of the Xiangjiang River, the population density surrounding parks in the eastern sector of the Xiangjiang River, except the central urban area, needs to be more extensive. This demographic distribution significantly contributes to the overall low vitality observed in the parks of this eastern region.

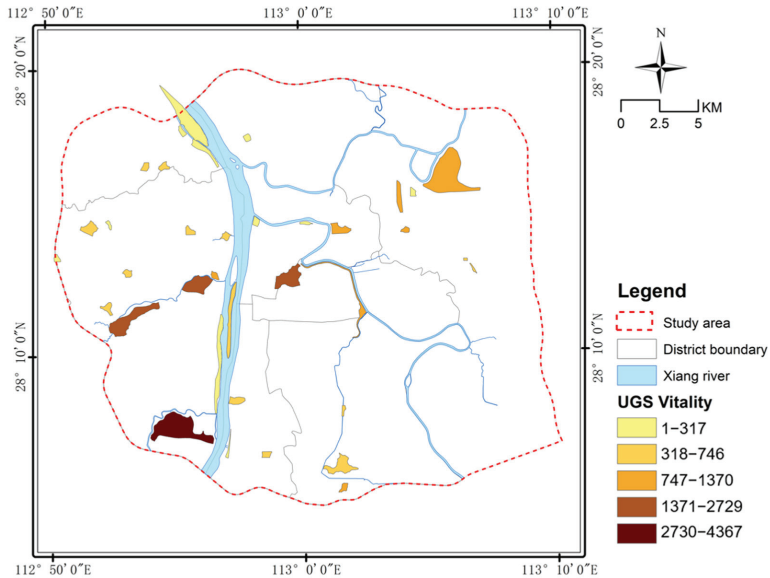

Figure 5. UGS Vitality analysis in Changsha.

4.2. Statistical Tests

As shown in Tables 3 and 4, the global model generated a high R^2, thereby substantiating that a significant proportion of park vitality can be elucidated by the independent variables chosen in this study. All VIF values of the elected independent variables are below 7.5, suggesting an absence of prominent collinearity problems among the independent variables. Given the study's relatively small number of observation points ($n = 65$), a t-test was used to ascertain statistical significance. A t-test value of 1.96 was established. The findings demonstrate that only the internal commercial facilities of the UGS exhibit statistical significance. The relative lack of statistical significance could be attributable to spatial heterogeneity, manifesting in inconsistent internal and external facilities across parks of divergent types, regions, and sizes. Moreover, the primary audience attracted by each park varies, leading to a reduction in statistical significance. A review of the aforementioned data reveals that the most influential factor with statistical significance is the internal commercial facilities of the park, showing a robust positive correlation with park vitality. Following this are the UGS's internal sports facilities and external public buildings. Conversely, the most significant negative correlation factor is the open space facilities within the UGS, trailed by the park's external transport facilities and dining establishments.

Table 3. OLS analysis result.

Variable	Coefficients	*p*-Value	t-Value	VIF
Intercept	112.44	1.00	1.43	n/a
		Internal Facilities		
Open space	−16.50	0.065	−1.86	3.82
Sports facilities	25.16	0.445	1.16	1.96
Entrance/Exit	15.94	0.551	0.607	5.89
Public Toilet	27.69	0.391	0.96	7.11
Business	35.77	0.001 **	3.89	4.00
		External Facilities		
Residential communities	1.67	0.111	1.53	3.05
Transportation facilities	−3.73	0.827	−0.19	2.78
Eateries	1.17	0.460	0.70	2.77
Companies	1.56	0.451	0.74	1.72
Public infrastructure	19.65	0.293	1.29	1.87

** Correlation is significant at the 0.01 level.

Table 4. Comparison of three analysis models.

	OLS	GWR	MGWR
R^2	0.745	0.854	0.854
Adjust R^2	0.698	0.794	0.801
AIC	117.601	98.477	95.383
AICc	125.601	116.369	110.270

4.3. Spatial Heterogeneity Analysis of Impact Factors

This investigation has implemented three statistical methodologies, namely OLS, GWR, and MGWR, to analyze the intricate relationship between UGS vitality and a spectrum of internal and external determinants (Table 4). These models allow us to dissect the research problem from varying angles and granularities, thus bestowing us a more holistic understanding of the factors shaping park vitality and their corresponding impact levels. The findings from each model will be meticulously dissected in the following in-depth analyses to decipher the implications and influences of these results for the research into park vitality and the practical sphere of UGS planning.

The OLS results operate on the premise that the influence of independent variables on the static state of park vitality within the research locale is acknowledged. However, in the context of spatial heterogeneity, the implementation of GWR was chosen for our investigation. In comparison to the OLS model, which yielded an R^2 of 0.745 and an AIC of 117.601, the GWR model enhanced the R^2 to 0.854 and reduced the AIC to 98.477. Moreover, the MGWR model, transcending the fixed bandwidth constraints of GWR, is also incorporated into this study. Despite no change in its R^2 the adjusted R^2 ascended from 0.794 in GWR to 0.801, coupled with a decrease in AIC from 98.477 in GWR to 95.383. The GWR model, vis-à-vis the OLS model, furnishes a more nuanced picture by augmenting model fitting and minimizing the information criterion, thereby unveiling potential divergent relationships between park vitality and its influencers across varying geographical locations. The MGWR model, surpassing the limitations of GWR, designates the optimal bandwidth for each explanatory variable individually, facilitating a more detailed examination of the spatial heterogeneity of each influence factor. Hence, on the whole, MGWR emerges as more befitting for the research at hand.

Table 5 reveals a notable discrepancy in bandwidth search between the internal commercial facilities of parks and the residential neighborhoods, whereas the bandwidths for other impact factors remain identical. This could suggest that in the research area, the internal commercial facilities of parks and the facilities in residential neighborhoods external to the parks exhibit a more significant density difference compared to other independent variables, necessitating different bandwidths for processing. Given the slight bandwidth difference between MGWR and GWR, their adjusted R^2 value and AIC differences are similarly minimal. However, this still sufficiently demonstrates the superior applicability of the MGWR model to this study.

Table 5. Both MGWR and GWR rely on adaptive bandwidth for their calculations.

	GWR	MGWR
	Internal Facilities	
Open space	63.000	62.000
Sports facilities	63.000	64.000
Entrance/Exit	63.000	64.000
Public Toilet	63.000	62.000
Business	63.000	45.000
	External Facilities	
Residential communities	63.000	51.000
Transportation facilities	63.000	64.000
Eateries	63.000	64.000
Companies	63.000	64.000
Public infrastructure	63.000	64.000

4.3.1. Internal Factors

The spatial distribution of the estimated coefficients of the internal variables selected is depicted in Figure 6, where different colors represent the impact of various factors on the vitality of UGS. From the results of the MGWR model, the internal influencing factors show significant regional differences in their impact on the vitality of Changsha's UGS; that is, spatial non-stationarity exists.

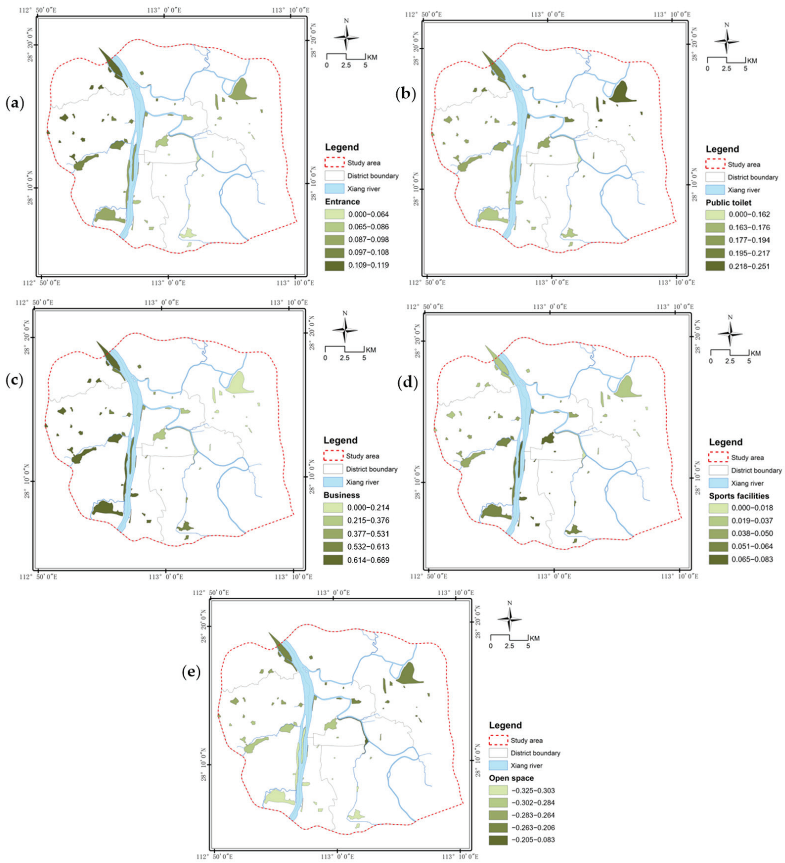

Figure 6. Spatial heterogeneity analysis of internal factors influencing park vitality: (**a**) entrance; (**b**) public toilet; (**c**) business; (**d**) sport facilities; (**e**) open space.

Looking at the results of each influencing factor, these variables show spatial heterogeneity in their impact on UGS vitality in different regions. For example, business and public toilets positively correlate with the dependent variable. In contrast, open space has a negative correlation with UGS vitality. In addition, the effects of sports facilities, entrances, and exits on vitality show similar trends, with significant differences in spatial distribution.

In terms of the influence of internal business on UGS vitality, the southwestern region demonstrates a stronger positive correlation compared to the central urban and northeastern areas. Due to the relatively recent development of Changsha County in the northeast region, the divergent trends between the southwestern and northeastern sectors suggest that urban parks in the southwest area of Changsha are more effective at attracting visitors and stimulating park vitality through their business, like catering and commercial features. Interestingly, data indicates that the presence of public toilets, which also positively correlates with urban park vitality, exerts a significantly more substantial impact in the northeastern and central city regions than in the southwestern region, signifying that the influence of public toilets on park vitality contrasts starkly with that of business on spatial vitality.

The effects of sports facilities and entrance–exit points on urban park vitality do not exhibit a uniformly positive correlation across different spatial distributions. For example, sports facilities mainly promote the park's vitality in the central area along the Xiang River in eastern Changsha. As they move away from the Xiang River, their effects tend to decrease. However, the beneficial impact of entrance and exit points on enhancing the vitality of UGS is mainly reflected in the northwest area of Changsha, which gradually decreases from north to south.

4.3.2. External Factors

In the context of external indicators (Figure 7), our analysis identified three significant factors—the presence of external public facilities, residential communities, and nearby companies—all of which predominantly demonstrate a positive correlation with the vitality of UGS in Changsha City. Regarding the impact of external transportation facilities on park vitality, although they have a common inhibitory effect on vitality, their spatial distribution differs from that of external catering facilities and enterprises. The influence in the Northeast is significantly more potent than in the central city and southwest. In addition, residential community factors have the most substantial impact on park vitality, with the overall pattern showing a high in the west and a low in the east.

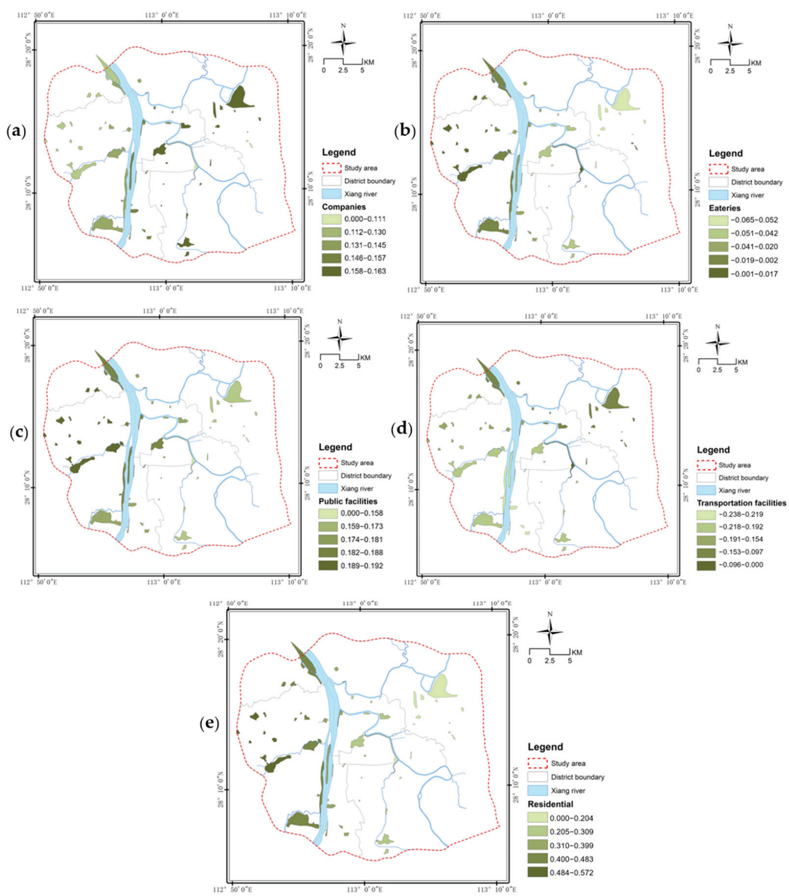

Figure 7. Spatial heterogeneity analysis of external factors influencing park vitality: (**a**) companies; (**b**) eateries; (**c**) public facilities; (**d**) transportation facilities; (**e**) residential.

5. Discussions

A deep understanding of the interplay between the vitality of UGS and their associated influencing factors bears considerable relevance for our nuanced appreciation of urban development and its "micro" environmental contexts. Notably, existing investigations focus on the holistic vitality of urban green spaces, often neglecting the spatial non-stationarity of their influential factors. Consequently, these studies generally employ an "average" to represent the weight of the influencing factors on the vitality of a city's green spaces, be they comprehensive, specific, or regional, thereby suggesting updated strategic approaches. However, shifts in the surrounding milieu may render the results derived from global models inapplicable to particular parks. This critical observation underpins the motivation for exploring the spatial heterogeneity of the factors affecting park vitality.

5.1. Accuracy Improvement of UGS Vitality Assessment

The use of MGWR necessitates an extensive amount of observational point data, and its integration with network information big data can maximize the advantages inherent in each. On the one hand, alongside economic and societal advancement, the utilization of mobile phones and their social applications is on the rise. The spatial vitality, represented as a dependent variable, is quantified by the count of individuals accessing the network within a given area, providing a more realistic representation of spatial vitality [85]. On the other hand, POI data with spatial location enables an effective enumeration of spatial vitality influencing factors within the research boundary. Consequently, the employment of MGWR to compute and scrutinize big data with spatial location attributes is predicted to yield superior fitting outcomes compared to both global and GWR models. This assertion has been corroborated across various disciplines [39–41].

This investigation employs a suite of analytical models, namely the OLS, GWR, and MGWR, to meticulously probe the intricate nexus between park vitality and an array of intrinsic and extrinsic determinants. It entails a comparative evaluation of the UGS activity simulations yielded by these distinct models. The MGWR model distinguishes itself by exhibiting heightened sensitivity to spatial heterogeneity and robust multi-scale analytical capabilities within this analytical framework. These attributes contribute substantially to the enhancement of model fitting and precision. This enhancement is quantitatively evidenced by a marked increment in the adjusted R^2 value, which ascends to 0.801, and a concurrent reduction in the AIC to 95.383, thereby affirming the superior performance of the MGWR model over its OLS and GWR counterparts in capturing the dynamics of UGS vitality.

The MGWR model's prowess lies in its capacity to discern and elucidate nuanced disparities in the spatial distribution of diverse influencing elements, including, but not limited to, internal commercial amenities within parks and adjacent external real estate developments. This capability accentuates the regional specificity and local nuances of these variables. By meticulously calibrating the optimal bandwidth for each explanatory variable, the MGWR model transcends the mere representation of spatial heterogeneity in park vitality. It profoundly augments the model's proficiency in elucidating and predicting park vitality's spatial dynamics. Consequently, given its pronounced efficacy in unraveling complex spatial interrelations and elevating simulation precision, the MGWR model is unequivocally validated as the preeminent methodological choice for this research endeavor.

This study takes Changsha, China as a case to explore the spatial heterogeneity of urban park vitality and its influencing factors. Interestingly, from the perspective of spatial heterogeneity, the findings of this study are consistent with the results of research in other regions of the world, such as sports facilities in Melbourne parks [86], commercial facilities in Shanghai parks [87], sports facilities and open spaces in Singapore studies [77], and public transportation in Seoul studies [88]. However, this study breaks through the scale limitations of traditional research, allowing for a more precise description of the differences in park vitality and its influencing factors in different urban areas. Additionally, the vitality of parks in Changsha and their influencing factors are significantly impacted by economic activities, which contrasts sharply with characteristics such as racial segregation in the United States [67], immigration issues in European cities [68], or urban expansion in Australia [69], reflecting the specificity of this study. Nevertheless, the universality is manifested in that the vitality of parks and their influencing factors in different regions all exhibit variations due to social, racial, economic, cultural, and other factors. Therefore, this study not only provides profound insights into the spatial heterogeneity of park vitality in Changsha but also offers important references and inspirations for other regions studying the spatial heterogeneity of park vitality and its influencing factors.

Overall, the determinants influencing urban park vitality do not manifest uniform impacts across disparate spatial domains [89,90]. In the context of the evolving urban and economic landscape, examining elements influencing urban park vitality necessitates the incorporation of dynamic perspectives. The MGWR model, in comparison to its counterparts, is particularly adept at capturing the spatial non-stationarity inherent in factors affecting urban park vitality. It comprehensively accounts for spatial heterogeneity, thereby facilitating the attainment of simulations more aligned with empirical realities. This nuanced approach ensures that the model reflects the spatially variable nature of influencing factors and underscores the dynamic interplay of these factors within the urban fabric, resulting in a more nuanced and authentic representation of UGS vitality.

5.2. Effect of Urban Spatial Structure on the Heterogeneity of UGS Vitality

Considering the urban spatial structure, the trajectory of commerce and sports facilities' development in Changsha City has been profoundly dictated by its inherent geographical conditions.

Traditionally, Changsha's bustling commercial zones have predominantly unfurled along the banks of the Xiang River. As the ancient city walls were dismantled and large-scale road infrastructures were erected in modern times, there was a notable southeastward shift and expansion of the city's area and populace. This shift became particularly pronounced post-2000, with the urban residential areas gradually moving eastward following the successful completion of the Wuyi Avenue expansion project. The current urban planning strategy, an iteration of the 2014 blueprint, revolves around the "Wuyi square" central axis and multiple auxiliary centers evolving synchronously. This strategic approach has given rise to mature urban sections like Yuelu University Science and Technology City and Huangxing Commercial Sub-center.

Under this framework, the western region is home to a cluster of universities, a predominantly young and middle-aged demographic, and comprehensively outfitted campus sports facilities. Conversely, the eastern region leans heavily towards commercial shopping, fostering a vibrant tourism economy with commercial streets densely interspersed. This stark contrast in the business orientation and demographic profile of Changsha's Xiang riverbanks prompts noticeable discrepancies in the impact and correlation of the internal metrics on the vitality of the city's eastern and western divisions. This nuanced observation underscores the heterogeneous nature of UGS preferences across different city regions.

The results unveiled by the MGWR bolster a trend wherein the variables under study depict pronounced heterogeneity in their influences on urban park vitality across spatial distribution, with each singular variable showcasing a clear linear trend within the urban spatial distribution. For instance, dining and shopping positively correlate with urban park vitality, with their influence intensifying from northeast to southwest in spatial distribution—a pattern echoed by other metrics. This insinuates the crucial role of urban location in impacting the efficacy of dependent variables on park vitality, thus underlining that any renewal strategies for Changsha's UGS must prioritize the variability of a single factor's influence on park vitality across diverse regions.

These results likely arise from differences in population demographics, economic composition, and transportation conditions among varying regions. For instance, Changsha exhibits a balanced pattern in the city center, with stark job-residential separation in the city outskirts [91]. The westward Yuelu District has universities, implying a broad educational distribution. The eastern Furong District—hosting Wuyi Square, Yuanjialing, and the railway station also presents its commercial structure's highest concentration of large-scale integrated shopping centers. Such findings further underline the significance of examining spatial heterogeneity in UGS usage for subsequent construction.

5.3. Heterogeneous Differences in Factors Affecting UGS Vitality

The analytical outcomes derived from the MGWR model's assessment of factors impacting UGS vitality are comprehensively tabulated in Table 6. Notably, within the ambit of internal indicators' influence on vitality, open spaces predominantly correlate negatively with the vitality of urban green spaces in Changsha City. This finding diverges from established research paradigms yet does not inherently contradict other scholarly works that identify a positive linkage between open spaces and spatial vitality. In this context, 'open space' pertains to areas within urban parks designated for activities such as rest, social interaction, and other quotidian engagements, encompassing plazas, open grasslands, and sheltered bridges. Prior research predominantly pivots on the premise that open spaces foster interpersonal interactions and pauses, concluding a psychological experiential perspective. While prevailing studies advocate that open spaces are instrumental in attracting individuals, the empirical observations in actual park design suggest that an overabundance of open spaces may inadvertently lead to the dispersal of individuals, thereby attenuating the vibrancy of these spaces. This phenomenon aligns with the insights garnered from previous scholarly investigations [75].

Table 6. Summary statistics for MGWR parameter estimates.

Variable	Mean	STD	Min	Median	Max
Intercept	0.000	0.015	0.026	−0.004	0.040
		Internal Facilities			
Business	0.514	0.175	0.158	0.595	0.674
Open spaces	−0.280	0.034	−0.328	−0.284	−0.206
Sports facilities	0.048	0.017	0.014	0.046	0.083
Entrance/Exit	0.091	0.017	0.055	0.090	0.119
Public Toilet	0.183	0.030	0.146	0.175	0.251
		External Facilities			
Residential communities	0.364	0.122	0.183	0.370	0.572
Transportation facilities	−0.179	0.042	−0.238	0.187	−0.097
Eateries	−0.026	0.025	−0.065	−0.027	0.017
Companies	0.133	0.023	0.090	0.135	0.163
Public infrastructure	0.172	0.013	0.145	0.173	0.192

Contrastingly, amenities such as catering and commercial facilities serve as focal points for congregation, thereby amplifying the density of spatial vitality. This phenomenon underpins the observed positive correlation between indicators of catering businesses and park vitality in internal assessments. A noteworthy observation from the study is the predominantly positive correlation between the selected dependent variables and the northeastern quadrant of the study area. This pattern may be intricately linked to the temporal dynamics of urban development. Relative to the central urban core and the southwestern district, the northeastern sector is a later entrant in urban evolution, characterized by comparatively lower population density and infrastructural development. This area's burgeoning demographic, fueled by urban–rural migration and the swift expansion of suburbs and emergent towns, has precipitated an escalating demand for multifunctional UGS. This trend underscores the heightened necessity for amenities within parks, resonating with the community's evolving requirements. The observed correlation suggests that the internal park facilities, as delineated in the study, play a pivotal role in catalyzing the vitality of green spaces in the northeastern region. The research findings imply that the construction of internal indices, as conceptualized and implemented in this study, is instrumental in nurturing and enhancing the vibrancy of local green spaces, particularly in the burgeoning northeastern areas, thereby underscoring the efficacy of strategic amenity placement in fostering dynamic and lively UGS.

Previous research hinged on the notion that open spaces stimulate interpersonal interaction and dwell time, emphasizing psychosocial perception-based results [27,59,79]. Despite the conventional wisdom that open spaces effectively draw crowds, actual park development with a surplus of open spaces could lead to an overdispersion of individuals, suppressing vitality and aligning with prior investigations [75]. Conversely, dining and commercial facilities that can effectively concentrate people and elevate spatial vitality density may explain why such indices positively correlate with park vitality internally [74]. Notably, the selected dependent variables generally correlate positively with the northeastern region, potentially linked to its developmental timeline. Relative to the central and southwestern districts, the northeast experienced delayed development, with its population density and infrastructure level being relatively low. However, with the surge in urban-rural migration in recent years, rapidly expanding suburbs and newly developed towns face an escalating demand for multifunctional UGS.

Consequently, the higher demand for UGS infrastructure among participants suggests that the selected internal metrics could effectively kindle green space vitality in the northeastern region. As observed from the external factors, the vitality of UGS in Changsha City predominantly hinges on elements such as public infrastructure, external eateries, housing communities, and companies. This observation aligns seamlessly with prior studies [87,92,93], reiterating that residents from neighboring communities and corporate personnel persist as the primary contributors to UGS. Particularly in the northeast, the presence of companies significantly bolsters vitality. This might be attributed to this region's dense concentration of industries and vocational institutions, where personnel from surrounding companies form a crucial segment of UGS participants.

Concurrently, the south witnesses a notable concentration of municipal public infrastructures, contributing more significantly to UGS vitality. While transportation facilities seemingly exert a suppressive impact on UGS vitality across all areas, their inhibitory influence is comparatively less pronounced in the northeast, indicating the indispensable nature of public transportation facilities, such as subway stations, particularly for urban parks farther from the city center. The suppressive role of transportation facilities on UGS vitality can be deciphered from the spatial patterns of Changsha's job–housing distribution, which is marked by significant commuting distance and time disparities. With a high frequency of population movement and dense residential communities, especially in the southwest, which has a dearth of office facilities, the problem of job-housing segregation becomes pronounced. This intensifies the commuting pressures on residents, thereby triggering a negative impact on park vitality—an effect most conspicuous in the southwest. Conversely, in the southeast and northeast regions, public infrastructure and businesses have effectively addressed local employment concerns, thereby centralizing job-housing and minimizing the impact of commuting.

In summary, findings from the MGWR study underline the considerable spatial variations in how the chosen independent variables influence the vitality of UGS. From an urban developmental history perspective, the increasing urban migration and peripheral expansion have amplified the differential manifestations of urban population characteristics, economic conditions, and transportation facilities across various urban regions. These evolving regional disparities and urban growth have resulted in heterogeneous park space needs, further echoed in the diverse promoting effects of different built environment indicators on UGS vitality. The diversity of parkgoers and the evolving nature of the surrounding built environments necessitate a fresh evaluation of the varied roles of different indices in stimulating park vitality during the construction of urban parks in diverse regions.

6. Conclusions

This study innovatively utilizes the MGWR model and multi-source big data, including Baidu Huiyan vitality data and Amap geospatial data, to investigate the spatial vitality of urban green spaces at the city scale. The research reveals marked spatial heterogeneity in factors influencing park vitality across diverse urban sectors, providing insights into intricate spatial patterns and dependencies between park vitality, residential communities, and commercial amenities. This methodological advancement beyond traditional frameworks enhances precision in assessing UGS vitality, offering valuable guidance for urban planners and policymakers. The study highlights the importance of recognizing and incorporating spatial heterogeneity in urban park planning, catering to dynamic urban evolution and economic development levels.

Furthermore, the methodologies and outcomes of this study hold considerable importance for park planning in Chinese urban centers, particularly Changsha, and offer novel perspectives and tools for investigating park vitality in other international cities. By examining the characteristics and determinants of park vitality across various countries and regions, this research contributes to a deeper comprehension of the global patterns and regional disparities in urban green space vitality. Consequently, it provides valuable references for planning and managing urban green spaces worldwide.

The research highlights factors influencing UGS vitality, both internal and external facilities, in Changsha's case study. These factors exhibit non-uniform spatial distributions, such as eateries impacting more from the northeast to the southwest, while sports facilities show an east–west divergence. The MGWR model outperforms traditional ones, offering nuanced insights for tailored UGS strategies. The study suggests prioritizing multifunctional UGS in Changsha's northeast for enhanced vitality, emphasizing minimal influence from augmenting transportation infrastructure. A customized approach is advocated for addressing specific human resource needs in different areas.

The limitations of our study primarily stem from potential inaccuracies in spatial vitality data due to errors in data location features and potential underrepresentation of particular demographic groups, notably older people and children. There is a recommendation to explore and implement novel data collection methods to address these limitations in future research. Such efforts aim to ensure a more comprehensive and representative dataset, ultimately enhancing the precision of UGS updates, fostering improved park environments, and contributing positively to urban dwellers' overall quality of life.

Author Contributions: Conceptualization, L.Q. and W.Z.; methodology, L.Q. and W.Z.; software, L.Q. and W.Z.; validation, L.Q., W.Z. and K.P.; formal analysis, L.Q. and K.P.; investigation, L.Q. and W.Z.; resources, R.Z.; data curation, W.Z.; writing—original draft preparation, L.Q., W.Z. and K.P.; writing—review and editing, R.Z.; visualization, W.Z.; supervision, R.Z.; project administration, R.Z.; funding acquisition, R.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Department of Natural Resources of Hunan Province for a major science and technology project "Research on Key Technologies of Land Spatial Planning and Monitoring and Supervision in Hunan Province" (202201) and National Natural Science Foundation of China (No. 52278059).

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

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

References

1. Wang, X.-J. Analysis of problems in urban green space system planning in China. *J. For. Res.* **2009**, *20*, 79–82. [CrossRef]
2. Liu, C.; Cao, M.; Yang, T.; Ma, L.; Wu, M.; Cheng, L.; Ye, R. Inequalities in the commuting burden: Institutional constraints and job-housing relationships in Tianjin, China. *Res. Transp. Bus. Manag.* **2022**, *42*, 100545. [CrossRef]
3. Zhang, Y.; Mao, W.; Zhang, B. Distortion of government behaviour under target constraints: Economic growth target and urban sprawl in China. *Cities* **2022**, *131*, 104009. [CrossRef]
4. Park, S.H.; Petrunoff, N.A.; Wang, N.X.; van Dam, R.M.; Sia, A.; Tan, C.S.; Müller-Riemenschneider, F. Daily park use, physical activity, and psychological stress: A study using smartphone-based ecological momentary assessment amongst a multi-ethnic Asian cohort. *Ment. Health Phys. Act.* **2022**, *22*, 100440. [CrossRef]
5. Deng, Z.; Chen, Y.; Yang, J.; Causone, F. AutoBPS: A Tool for Urban Building Energy Modeling to Support Energy Efficiency Improvement at City-Scale. *Energy Build.* **2023**, *282*, 112794. [CrossRef]
6. Martins, B. Where to construct new urban green spaces to be at the recommended distance from users and to complement existing ones? A study in five cities of northern Portugal. *Urban For. Urban Green.* **2022**, *72*, 127571. [CrossRef]

7. Wang, J.; Zhang, Y.; Zhang, X.; Song, M.; Ye, J. The spatio-temporal trends of urban green space and its interactions with urban growth: Evidence from the Yangtze River Delta region, China. *Land Use Policy* **2023**, *128*, 106598. [CrossRef]
8. Montgomery, J. Making a city: Urbanity, vitality and urban design. *J. Urban Des.* **1998**, *3*, 93–116. [CrossRef]
9. Jacobs, J. *The Death and Life of Great American Cities. The Failure of Town Planning*; The Ohio State University Press: New York, NY, USA, 1961; p. 71.
10. Zhang, Z.; Xiao, Y.; Luo, X.; Zhou, M. Urban human activity density spatiotemporal variations and the relationship with geographical factors: An exploratory Baidu heatmaps-based analysis of Wuhan, China. *Growth Change* **2020**, *51*, 505–529. [CrossRef]
11. Yang, J.; Deng, Z.; Guo, S.; Chen, Y. Development of Bottom-up Model to Estimate Dynamic Carbon Emission for City-Scale Buildings. *Appl. Energy* **2023**, *331*, 120410. [CrossRef]
12. Veitch, J.; Ball, K.; Rivera, E.; Loh, V.; Deforche, B.; Best, K.; Timperio, A. What entices older adults to parks? Identification of park features that encourage park visitation, physical activity, and social interaction. *Landsc. Urban Plan.* **2022**, *217*, 104254. [CrossRef]
13. Park, K.; Ewing, R. The usability of unmanned aerial vehicles (UAVs) for measuring park-based physical activity. *Landsc. Urban Plan.* **2017**, *167*, 157–164. [CrossRef]
14. Lis, A.; Zalewska, K.; Pardela, Ł.; Adamczak, E.; Cenarska, A.; Bławicka, K.; Brzegowa, B.; Matiiuk, A. How the amount of greenery in city parks impacts visitor preferences in the context of naturalness, legibility and perceived danger. *Landsc. Urban Plan.* **2022**, *228*, 104556. [CrossRef]
15. Shi, P.; Xiao, Y.; Zhan, Q. A Study on spatial and temporal aggregation patterns of urban population in wuhan city based on baidu heat map and POI data. *Int. Rev. Spat. Plan. Sustain. Dev.* **2020**, *8*, 101–121. [CrossRef] [PubMed]
16. Chuang, I.-T.; Benita, F.; Tunçer, B. Effects of urban park spatial characteristics on visitor density and diversity: A geolocated social media approach. *Landsc. Urban Plan.* **2022**, *226*, 104514. [CrossRef]
17. Huai, S.; Chen, F.; Liu, S.; Canters, F.; Van de Voorde, T. Using social media photos and computer vision to assess cultural ecosystem services and landscape features in urban parks. *Ecosyst. Serv.* **2022**, *57*, 101475. [CrossRef]
18. Liu, Y.; Hu, J.; Yang, W.; Luo, C. Effects of urban park environment on recreational jogging activity based on trajectory data: A case of Chongqing, China. *Urban For. Urban Green.* **2022**, *67*, 127443. [CrossRef]
19. Kong, L.; Liu, Z.; Pan, X.; Wang, Y.; Guo, X.; Wu, J. How do different types and landscape attributes of urban parks affect visitors' positive emotions? *Landsc. Urban Plan.* **2022**, *226*, 104482. [CrossRef]
20. Roberts, H.V. Using Twitter data in urban green space research: A case study and critical evaluation. *Appl. Geogr.* **2017**, *81*, 13–20. [CrossRef]
21. Lang, W.; Lang, H.; Hui, E.C.M.; Chen, T.; Wu, J.; Jahre, M. Measuring urban vibrancy of neighborhood performance using social media data in Oslo, Norway. *Cities* **2022**, *131*, 103908. [CrossRef]
22. Veitch, J.; Carver, A.; Abbott, G.; Giles-Corti, B.; Timperio, A.; Salmon, J. How active are people in metropolitan parks? An observational study of park visitation in Australia. *BMC Public Health* **2015**, *15*, 1–8. [CrossRef] [PubMed]
23. Oshan, T.M.; Fotheringham, A.S. A Comparison of Spatially Varying Regression Coefficient Estimates Using Geographically Weighted and Spatial-Filter-Based Techniques. *Geogr. Anal.* **2018**, *50*, 53–75. [CrossRef]
24. Fotheringham, A.S.; Yang, W.; Kang, W. Multiscale geographically weighted regression (MGWR). *Ann. Am. Assoc. Geogr.* **2017**, *107*, 1247–1265. [CrossRef]
25. Forati, A.M.; Ghose, R.; Mantsch, J.R. Examining Opioid Overdose Deaths across Communities Defined by Racial Composition: A Multiscale Geographically Weighted Regression Approach. *J. Urban Health* **2021**, *98*, 551–562. [CrossRef] [PubMed]
26. Foresman, T.; Luscombe, R. The second law of geography for a spatially enabled economy. *Int. J. Digit. Earth* **2017**, *10*, 979–995. [CrossRef]
27. Samsudin, R.; Yok, T.P.; Chua, V. Social capital formation in high density urban environments: Perceived attributes of neighborhood green space shape social capital more directly than physical ones. *Landsc. Urban Plan.* **2022**, *227*, 104527. [CrossRef]
28. Tobler, W. On the first law of geography: A reply. *Ann. Assoc. Am. Geogr.* **2004**, *94*, 304–310. [CrossRef]
29. Cao, X.; Shi, Y.; Zhou, L.; Tao, T.; Yang, Q. Analysis of factors influencing the urban carrying capacity of the shanghai metropolis based on a multiscale geographically weighted regression (MGWR) model. *Land* **2021**, *10*, 578. [CrossRef]
30. Sisman, S.; Aydinoglu, A.C. A modelling approach with geographically weighted regression methods for determining geographic variation and influencing factors in housing price: A case in Istanbul. *Land Use Policy* **2022**, *119*, 106183. [CrossRef]
31. Chien, Y.-M.C.; Carver, S.; Comber, A. Using geographically weighted models to explore how crowdsourced landscape perceptions relate to landscape physical characteristics. *Landsc. Urban Plan.* **2020**, *203*, 103904. [CrossRef]
32. Zhou, Q.; Wang, C.; Fang, S. Application of geographically weighted regression (GWR) in the analysis of the cause of haze pollution in China. *Atmos. Pollut. Res.* **2019**, *10*, 835–846. [CrossRef]
33. Senyel Kurkcuoglu, M.A. Analysis of the energy justice in natural gas distribution with Multiscale Geographically Weighted Regression (MGWR). *Energy Rep.* **2023**, *9*, 325–337. [CrossRef]
34. Permai, S.D.; Christina, A.; Gunawan, A.A.S. Fiscal decentralization analysis that affect economic performance using geographically weighted regression (GWR). *Procedia Comput. Sci.* **2021**, *179*, 399–406. [CrossRef]
35. Wu, D. Spatially and temporally varying relationships between ecological footprint and influencing factors in China's provinces Using Geographically Weighted Regression (GWR). *J. Clean. Prod.* **2020**, *261*, 121089. [CrossRef]

36. Chen, T.-L.; Lin, Z.-H. Impact of land use types on the spatial heterogeneity of extreme heat environments in a metropolitan area. *Sustain. Cities Soc.* **2021**, *72*, 103005. [CrossRef]
37. Cohen, D.A.; Marsh, T.; Williamson, S.; Derose, K.P.; Martinez, H.; Setodji, C.; McKenzie, T.L. Parks and physical activity: Why are some parks used more than others? *Prev. Med.* **2010**, *50*, S9–S12. [CrossRef] [PubMed]
38. McCormack, G.R.; Rock, M.; Toohey, A.M.; Hignell, D. Characteristics of urban parks associated with park use and physical activity: A review of qualitative research. *Health Place* **2010**, *16*, 712–726. [CrossRef] [PubMed]
39. Xue, C.; Chen, X.; Xue, L.; Zhang, H.; Chen, J.; Li, D. Modeling the spatially heterogeneous relationships between tradeoffs and synergies among ecosystem services and potential drivers considering geographic scale in Bairin Left Banner, China. *Sci. Total. Environ.* **2023**, *855*, 158834. [CrossRef] [PubMed]
40. Lu, B.; Ge, Y.; Shi, Y.; Zheng, J.; Harris, P. Uncovering drivers of community-level house price dynamics through multiscale geographically weighted regression: A case study of Wuhan, China. *Spat. Stat.* **2023**, *53*, 100723. [CrossRef]
41. Mansour, S.; Al Kindi, A.; Al-Said, A.; Al-Said, A.; Atkinson, P. Sociodemographic determinants of COVID-19 incidence rates in Oman: Geospatial modelling using multiscale geographically weighted regression (MGWR). *Sustain. Cities Soc.* **2021**, *65*, 102627. [CrossRef] [PubMed]
42. Wu, C.; Ye, X.; Ren, F.; Du, Q. Check-in behaviour and spatio-temporal vibrancy: An exploratory analysis in Shenzhen, China. *Cities* **2018**, *77*, 104–116. [CrossRef]
43. Montgomery, J. Editorial Urban Vitality and the Culture of Cities. *Plan. Pract. Res.* **1995**, *10*, 101–110. [CrossRef]
44. Mohammed, A.; Khan, A.; Santamouris, M. Numerical evaluation of enhanced green infrastructures for mitigating urban heat in a desert urban setting. *Build. Simul.* **2023**, *16*, 1691–1712. [CrossRef]
45. Zhou, L.; Shi, Y.; Zheng, J. Business circle identification and spatiotemporal characteristics in the main urban area of yiwu city based on POI and night-time light data. *Remote Sens.* **2021**, *13*, 5153. [CrossRef]
46. Yue, Y.; Zhuang, Y.; Yeh, A.G.-O.; Xie, J.-Y.; Ma, C.-L.; Li, Q.-Q. Measurements of POI-based mixed use and their relationships with neighbourhood vibrancy. *Int. J. Geogr. Inf. Sci.* **2017**, *31*, 658–675. [CrossRef]
47. Song, Y.; Huang, B.; Cai, J.; Chen, B. Dynamic assessments of population exposure to urban greenspace using multi-source big data. *Sci. Total. Environ.* **2018**, *634*, 1315–1325. [CrossRef] [PubMed]
48. Deng, Z.; Zhu, Y.; Liu, M.; Wang, S. Using Big Data for a Comprehensive Evaluation of Urban Vitality: A Case Study of Guangzhou, China. In Proceedings of the 2022 5th International Conference on Artificial Intelligence and Big Data (ICAIBD), Chengdu, China, 27–30 May 2022; pp. 361–368.
49. Gibbs, H.; Liu, Y.; Pearson, C.A.B.; Jarvis, C.I.; Grundy, C.; Quilty, B.J.; Diamond, C.; Eggo, R.M.; Simons, D.; Gimma, A.; et al. Changing travel patterns in China during the early stages of the COVID-19 pandemic. *Nat. Commun.* **2020**, *11*, 5012. [CrossRef] [PubMed]
50. Oshan, T.M.; Li, Z.; Kang, W.; Wolf, L.J.; Fotheringham, A.S. MGWR: A python implementation of multiscale geographically weighted regression for investigating process spatial heterogeneity and scale. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 269. [CrossRef]
51. Iyanda, A.E.; Osayomi, T. Is there a relationship between economic indicators and road fatalities in Texas? A multiscale geographically weighted regression analysis. *GeoJournal* **2021**, *86*, 2787–2807. [CrossRef]
52. Gong, S.; Cartlidge, J.; Bai, R.; Yue, Y.; Li, Q.; Qiu, G. Geographical and temporal huff model calibration using taxi trajectory data. *GeoInformatica* **2020**, *25*, 485–512. [CrossRef]
53. Soltani, A.; Pettit, C.J.; Heydari, M.; Aghaei, F. Housing price variations using spatio-temporal data mining techniques. *J. Hous. Built Environ.* **2021**, *36*, 1199–1227. [CrossRef]
54. Wang, Q.; Jiang, D.; Gao, Y.; Zhang, Z.; Chang, Q. Examining the Driving Factors of SOM Using a Multi-Scale GWR Model Augmented by Geo-Detector and GWPCA Analysis. *Agronomy* **2022**, *12*, 1697. [CrossRef]
55. Wang, X.; Zhang, Y.; Yu, D.; Qi, J.; Li, S. Investigating the spatiotemporal pattern of urban vibrancy and its determinants: Spatial big data analyses in Beijing, China. *Land Use Policy* **2022**, *119*, 106162. [CrossRef]
56. Pfiester, L.M.; Thompson, R.G.; Zhang, L. Spatiotemporal exploration of Melbourne pedestrian demand. *J. Transp. Geogr.* **2021**, *95*, 103151. [CrossRef]
57. Yujia, Z.; Chengzhao, W.U. Identification of Main Influencing Factors on Urban Park Overall Satisfaction: Based on Analysis of Users of Different Age Groups. *Landsc. Archit.* **2021**, *28*, 57–62.
58. Sen, A.; Nagendra, H. Local community engagement, environmental placemaking and stewardship by migrants: A case study of lake conservation in Bengaluru, India. *Landsc. Urban Plan.* **2020**, *204*, 103933. [CrossRef]
59. Voigt, A.; Kabisch, N.; Wurster, D.; Haase, D.; Breuste, J. Structural diversity: A multi-dimensional approach to assess recreational services in urban parks. *AMBIO* **2014**, *43*, 480–491. [CrossRef] [PubMed]
60. Veitch, J.; Ball, K.; Flowers, E.; Deforche, B.; Timperio, A. Children's ratings of park features that encourage park visitation, physical activity and social interaction. *Urban For. Urban Green.* **2021**, *58*, 126963. [CrossRef]
61. Lin, J.; Cromley, R.G. Evaluating geo-located Twitter data as a control layer for areal interpolation of population. *Appl. Geogr.* **2015**, *58*, 41–47. [CrossRef]
62. Longley, P.A.; Frank Goodchild, M. *Geographic Information Science and Systems. International Encyclopedia of Human Geography*, 2nd ed.; John Wiley & Sons: New York, NY, USA, 2019.
63. Shen, Y.; Karimi, K. Urban function connectivity: Characterisation of functional urban streets with social media check-in data. *Cities* **2016**, *55*, 9–21. [CrossRef]

64. Hao, P.; He, S. What is holding farmers back? Endowments and mobility choice of rural citizens in China. *J. Rural. Stud.* **2022**, *89*, 66–72. [CrossRef]
65. Shi, R.; Yeh, A.G.-O. Do similar social groups have similar mobility in a city? Social areas and mobility in Shenzhen, China. *Cities* **2023**, *138*, 104350. [CrossRef]
66. Gu, H.; Lin, Y.; Shen, T. Do you feel accepted? Perceived acceptance and its spatially varying determinants of migrant workers among Chinese cities. *Cities* **2022**, *125*, 103626. [CrossRef]
67. Osypuk, T.L.; Galea, S.; McArdle, N.; Acevedo-Garcia, D. Quantifying separate and unequal: Racial-Ethnic distributions of neighborhood poverty in metropolitan America. *Urban Aff. Rev.* **2009**, *45*, 25–65. [CrossRef] [PubMed]
68. Lichter, D.T.; Parisi, D.; Ambinakudige, S. The Spatial Integration of Immigrants in Europe: A Cross-National Study. *Popul. Res. Policy Rev.* **2020**, *39*, 465–491. [CrossRef]
69. James, A.; Rowley, S.; Davies, A.; ViforJ, R.O.; Singh, R. Population growth and mobility in Australia: Implications for housing and urban development policies. *AHURI Final. Rep.* **2021**, 82. [CrossRef]
70. Jiang, S.; Alves, A.; Rodrigues, F.; Ferreira, J., Jr.; Pereira, F.C. Mining point-of-interest data from social networks for urban land use classification and disaggregation. *Comput. Environ. Urban Syst.* **2015**, *53*, 36–46. [CrossRef]
71. Huang, L.; Li, Q.; Yue, Y. Activity identification from GPS trajectories using spatial temporal POIs attractiveness. In Proceedings of the 2nd ACM SIGSPATIAL International Workshop on Location Based Social Networks, San Jose, CA, USA, 2 November 2010. LBSN 2010-Held in Conjunction with ACM SIGSPATIAL GIS 2010.
72. Zhong, J.; Li, Z.; Sun, Z.; Tian, Y.; Yang, F. The spatial equilibrium analysis of urban green space and human activity in Chengdu, China. *J. Clean. Prod.* **2020**, *259*, 120754. [CrossRef]
73. Jia, T.; Ji, Z. Understanding the functionality of human activity hotspots from their scaling pattern using trajectory data. *ISPRS Int. J. Geo-Inf.* **2017**, *6*, 341. [CrossRef]
74. Zhou, C.; An, Y.; Zhao, J.; Xue, Y.; Fu, L. How do mini-parks serve in groups? A visit analysis of mini-park groups in the neighbourhoods of Nanjing. *Cities* **2022**, *129*, 103804. [CrossRef]
75. Lyu, F.; Zhang, L. Using multi-source big data to understand the factors affecting urban park use in Wuhan. *Urban For. Urban Green.* **2019**, *43*, 126367. [CrossRef]
76. Zhang, S.; Zhou, W. Recreational visits to urban parks and factors affecting park visits: Evidence from geotagged social media data. *Landsc. Urban Plan.* **2018**, *180*, 27–35. [CrossRef]
77. Petrunoff, N.A.; Edney, S.; Yi, N.X.; Dickens, B.L.; Joel, K.R.; Xin, W.N.; Sia, A.; Leong, D.; van Dam, R.M.; Cook, A.R.; et al. Associations of park features with park use and park-based physical activity in an urban environment in Asia: A cross-sectional study. *Health Place* **2022**, *75*, 102790. [CrossRef] [PubMed]
78. Zhang, R.; Zhang, C.-Q.; Lai, P.C.; Kwan, M.-P. Park and neighbourhood environmental characteristics associated with park-based physical activity among children in a high-density city. *Urban For. Urban Green.* **2022**, *68*, 127479. [CrossRef]
79. Oviedo, M.; Drescher, M.; Dean, J. Urban greenspace access, uses, and values: A case study of user perceptions in metropolitan ravine parks. *Urban For. Urban Green.* **2022**, *70*, 127522. [CrossRef]
80. Mu, B.; Liu, C.; Mu, T.; Xu, X.; Tian, G.; Zhang, Y.; Kim, G. Spatiotemporal fluctuations in urban park spatial vitality determined by on-site observation and behavior mapping: A case study of three parks in Zhengzhou City, China. *Urban For. Urban Green.* **2021**, *64*, 127246. [CrossRef]
81. Zhai, Y.; Li, D.; Wu, C.; Wu, H. Urban park facility use and intensity of seniors' physical activity—An examination combining accelerometer and GPS tracking. *Landsc. Urban Plan.* **2021**, *205*, 103950. [CrossRef]
82. L'Aoustet, O.; Griffet, J. The Experience of Teenagers at Marseilles' Skate Park: Emergence and Evaluation of an Urban Sports Site. *Cities* **2001**, *18*, 413–418. [CrossRef]
83. Mollalo, A.; Vahedi, B.; Rivera, K.M. GIS-based spatial modeling of COVID-19 incidence rate in the continental United States. *Sci. Total. Environ.* **2020**, *728*, 138884. [CrossRef]
84. Yu, H.; Fotheringham, A.S.; Li, Z.; Oshan, T.; Kang, W.; Wolf, L.J. Inference in Multiscale Geographically Weighted Regression. *Geogr. Anal.* **2020**, *52*, 87–106. [CrossRef]
85. Jin, M.; Gong, L.; Cao, Y.; Zhang, P.; Gong, Y.; Liu, Y. Identifying borders of activity spaces and quantifying border effects on intra-urban travel through spatial interaction network. *Comput. Environ. Urban Syst.* **2021**, *87*, 101625. [CrossRef]
86. Rivera, E.; Timperio, A.; Loh, V.H.Y.; Deforche, B.; Veitch, J. Critical factors influencing adolescents' active and social park use: A qualitative study using walk-along interviews. *Urban For. Urban Green.* **2021**, *58*, 126948. [CrossRef]
87. Huai, S.; Liu, S.; Zheng, T.; Van de Voorde, T. Are social media data and survey data consistent in measuring park visitation, park satisfaction, and their influencing factors? A case study in Shanghai. *Urban For. Urban Green.* **2023**, *81*, 127869. [CrossRef]
88. Lee, S.H.; Kang, J.E. Impact of particulate matter and urban spatial characteristics on urban vitality using spatiotemporal big data. *Cities* **2022**, *131*, 104030. [CrossRef]
89. Tu, W.; Zhu, T.; Xia, J.; Zhou, Y.; Lai, Y.; Jiang, J.; Li, Q. Portraying the spatial dynamics of urban vibrancy using multisource urban big data. *Comput. Environ. Urban Syst.* **2020**, *80*, 101428. [CrossRef]
90. Huang, Y.; Lin, T.; Zhang, G.; Zhu, Y.; Zeng, Z.; Ye, H. Spatial patterns of urban green space and its actual utilization status in China based on big data analysis. *Big Earth Data* **2021**, *5*, 391–409. [CrossRef]
91. Zhuoya, X.; Min, Y.; Yuhan, D.; Bin, D.; Xuan, T. The Exploration of the Jobs-Housing Relationship in Changsha Based on the Perspective of Big Data. *Chin. Overseas Archit.* **2019**, *4*, 59–62. [CrossRef]

92. Fan, Z.; Duan, J.; Lu, Y.; Zou, W.; Lan, W. A geographical detector study on factors influencing urban park use in Nanjing, China. *Urban For. Urban Green.* **2021**, *59*, 126996. [CrossRef]
93. Hamstead, Z.A.; Fisher, D.; Ilieva, R.T.; Wood, S.A.; McPhearson, T.; Kremer, P. Geolocated social media as a rapid indicator of park visitation and equitable park access. *Comput. Environ. Urban Syst.* **2018**, *72*, 38–50. [CrossRef]

land

Article

Conceptualisation of the Regulatory Framework of Green Infrastructure for Urban Development: Identifying Barriers and Drivers

Dragan Vujičić , Nevena Vasiljević , Boris Radić *, Andreja Tutundžić, Nevenka Galečić , Dejan Skočajić and Mirjana Ocokoljić

Faculty of Forestry, University of Belgrade, Kneza Viseslava 1, 11000 Beograd, Serbia;
dragan.vujicic@sfb.bg.ac.rs (D.V.); nevena.vasiljevic@sfb.bg.ac.rs (N.V.); andreja.tutundzic@sfb.bg.ac.rs (A.T.);
nevenka.galecic@sfb.bg.ac.rs (N.G.); dejan.skocajic@sfb.bg.ac.rs (D.S.); mirjana.ocokoljic@sfb.bg.ac.rs (M.O.)
* Correspondence: boris.radic@sfb.bg.ac.rs; Tel.: +381-1130-53942

Abstract: Urban green infrastructure plays a crucial role in sustainable city development by offering a multitude of benefits, including improved environmental quality, increased social well-being, and enhanced economic prosperity. Evaluation and monitoring of regulatory implementation stand as essential components in the advancement of urban green infrastructure (GI) as they indicate the efficacy of regulatory acts and enable the assessment of their implementation success and adaptability to identified needs. This study identifies barriers and drivers based on the views of 352 professionals surveyed between 2018 and 2023 in Serbia. The primary data collection method employed questionnaire surveys. This study identified a range of barriers within existing legal frameworks, foremost of which include the lack of coordination and coherence between relevant ministries and governmental agencies, insufficient financial and human resources, the lack of transparency in the regulation development process, the need for strengthening technical capacities, and the absence of an adequate urban GI strategy. This research serves as a foundation for conceptualising GI regulatory elements that enhance urban GI development. Addressing these barriers necessitates efforts to improve coordination and collaboration among stakeholders, increase public participation, and enhance transparency in the regulatory process.

Keywords: green infrastructure; conceptual framework; institutional innovation; green infrastructure regulation; ecosystem services

Citation: Vujičić, D.; Vasiljević, N.; Radić, B.; Tutundžić, A.; Galečić, N.; Skočajić, D.; Ocokoljić, M. Conceptualisation of the Regulatory Framework of Green Infrastructure for Urban Development: Identifying Barriers and Drivers. *Land* **2024**, *13*, 692. https://doi.org/10.3390/land13050692

Academic Editor: Thomas Panagopoulos

Received: 23 March 2024
Revised: 19 April 2024
Accepted: 27 April 2024
Published: 15 May 2024

1. Introduction

1.1. Theoretical Background

Rapid urbanisation across the planet has left a significant ecological footprint, resulting in profound changes to landscape patterns and ecosystem structures and functions. This trend ultimately leads to the degradation and fragmentation of natural and nature-like elements, undermining the integrity of landscapes. Moreover, it contributes to the emergence of urban heat islands, increased greenhouse gas emissions, and reduced biodiversity. Concurrently, there is an evident decline in health and well-being, which, combined with the effects of intense climate change, adversely affect the quality of life of residents of modern cities [1–4].

As the key driver of changes in the quality and integrity of environmental elements, urbanisation necessitates the adaptation of urban landscape planning models towards greater sustainability [5,6]. The concept of sustainability should primarily respect existing natural values within urban settings to determine new planning models based on landscape ecology principles that will enable the preservation of existing and the creation of new nature-like elements in the urban structure [7]. The planning model should, by no means, be viewed as a static instrument but be based on emerging knowledge regarding climate change and innovative approaches to sustainable planning; it should create a dynamic representation of the city as an adaptable organism that can provide space for the coexistence of nature and city residents [8]. Of course, planning the metropolitan areas of landscapes at the regional and global levels requires more than just having models based on scientific hypotheses that have been validated in local practice. It also requires having a sufficient regulatory framework to allow the process to be applied.

Green infrastructure has been identified as an effective measure to address many of the negative consequences of urbanisation and climate change and to improve the sustainability of urban development [9–11]. Urban landscapes are saturated with non-porous surfaces, which serve as the foundation for urban processes and functions. In this context, natural and nature-like elements fail to provide ecosystem services adequately and effectively. Green infrastructure is a concept that unites elements of different forms and spatial levels into a system that represents a conglomerate of ecosystem services capable of responding to the challenges posed by climate change, improving the environment, and ensuring the quality of life of city residents [12]. In addition, the efficient planning of GI elements, such as parks, tree-lined streets, blue–green corridors, recreational spaces, and individual trees, forms a resilient network that, through ecosystem services, promotes sustainable cities and provides an environmental platform for creating a smart city [13,14].

In light of the recognised value of the green infrastructure concept, governments worldwide are dedicating considerable efforts to integrate GI into their policy programs and planning guidelines [15]. This process is particularly aided by the emergence of the United Nations Sustainable Development Goals [16] set for 2030, underscoring the role of green infrastructure in achieving the goals related to conserving life on land (SDG 14), ensuring clean water (SDG 6), and adapting to climate change (SDG 13) [17]. However, research has confirmed the uneven presence and distribution of GI elements within the regulatory framework because of various factors. These include historical context, state policies aimed at increasing property value, financial constraints for GI maintenance and development, top-down political decisions and their implementation, and limited public involvement [8,18,19].

1.2. Development of the Conceptual Framework for Green Infrastructure

The concept of green infrastructure has been seeking its place within the regulatory framework of planning institutions and practices worldwide for decades. Presently, three informal phases of this process have been delineated [20]: the exploration phase, which occurred during the 1990s and primarily focused on uncoordinated scientific research on the ecological functions of green infrastructure to a limited extent; the expansion phase, which took place during the 2000s and initiated a broader discussion on the principles and values of green infrastructure; and the consolidation phase, which started around 2014, with earnest efforts to integrate green infrastructure into policy.

In the USA, this concept primarily materialised as blue–green infrastructure, serving the function of natural resource protection and water management, particularly at the urban scale [21]. Although larger cities, such as Boston, New York, and Philadelphia, as pioneers in this process, recognised the value of urban green spaces and integrated them into conservation efforts, this approach did not systematically influence other cities [22]. In recent decades, countries in Asia and the Global South have also been actively engaged in researching the impact of green infrastructure on the quality of urban landscapes and exploring modalities for the development of planning guidelines [23]. Within Europe, green infrastructure is embraced as both a spatial and functional concept, extensively covered in numerous reports and strategies. The presence of the ecological network concept rendered Europe as being fertile ground for the adoption of this new approach, with particular significance attributed to the EU Green Infrastructure Strategy. This strategy identifies green infrastructure as an integrated network of natural features that enhance the status and perception of ecosystem services across various sectors, including biodiversity preservation; climate adaptation; forestry, soil, and water protection; and the circular economy [24].

The advancement of the application of the concept of green infrastructure in the UK is particularly significant, given the long tradition of landscape and green area planning. Key principles supporting green infrastructure planning, along with proven methodologies, have been identified [25].

In previous research, green infrastructure has consistently demonstrated its capacity to address the challenges posed by modern city development and climate change across various scales, from global to local. It operates on principles such as multifunctionality, connectivity, diversity, and identity. However, one of the challenges lies in the comprehensive regulation of green infrastructure, as its spatial and functional coverage is vast and intertwined with geographical contexts [24,26].

Countries in transition, such as Serbia, face similar challenges stemming from territorial irregularities and uneven urban systems. For instance, Belgrade, Serbia's capital, hosts more than 15% of the country's urban population and serves as the centre for most urban functions, including finances, education, and culture [27]. In addition, the metropolitan area of Belgrade, along with other cities, accommodates more than half of Serbia's population but comprises less than 2% of all the settlements [28]. Consequently, Belgrade grapples with numerous environmental issues related to air quality, urban heat islands, flood occurrences, soil erosion, and the loss of biodiversity [29,30]. To address these challenges and integrate green infrastructure into urban development for a more sustainable, resilient, and healthier city, a systemic regulatory approach becomes imperative. Given its development, Belgrade serves as an ideal testing ground for the application of green infrastructure concepts, contributing to more effective protection, management, and restoration of urban ecosystems. Although Belgrade has a certain tradition regarding the city's natural values, dating back to the first urban plan in the late nineteenth century and the concept of the green belt introduced in the thirties of the twentieth century, a systemic framework for regulating green infrastructure has been notably absent until now.

The dogmatic approach represented in land use planning regulations reflects a specific law system influenced by traditional and cultural attitudes towards urban open spaces and their resources. Consequently, identifying a universal and inclusive approach to the development of green infrastructure regulations proves to be challenging. Moreover, decision-makers and planners crucial to regulation development often employ incoherent and uncoordinated strategies because of the abundance of literature and examples on green infrastructure models, coupled with the lack of clarity on regulatory development approaches and instruments [31]. The methodological framework of our study was established through the formation of a conceptual framework aimed at identifying barriers and drivers within a comprehensive scope. It is essential to form a consensus around the establishment of an organisational strategy capable for addressing all the questions regarding the treatment of green infrastructure elements. The initial construction of the applied approach relied on the models that were used and proved during the analysis of the modalities of the formation and success of the regulatory framework. These models relied on determining the viewpoints of professionals dealing with green infrastructure from different aspects and at different scales [32]. It is crucial to identify all the barriers, recognised by active professionals in the field, impeding the transformation of the spatial planning system and obstructing the institutionalisation of the green infrastructure concept [33]. To address this, a list of pertinent questions was formulated to highlight potential drivers identified by professionals directly or indirectly during their work [34].

This conceptual framework serves as the interconnection of different concepts and provides a comprehensive understanding of the integral role each concept plays within the network [35]. Detailed data collection and aggregation were essential for developing this framework. The conceptual framework, depicted in Figure 1, is based on knowledge derived from both theory and practice. These findings will contribute to the scientific discourse on green infrastructure and aid practitioners seeking to understand appropriate planning and design processes.

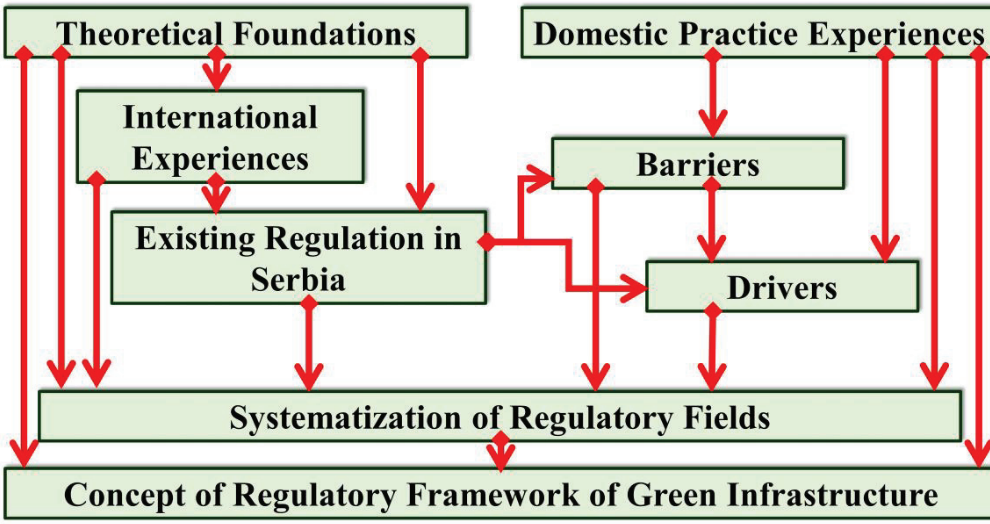

Figure 1. Dual approach in the study: theoretical foundations and practice.

Consequently, research conducted between 2018 and 2023 in Serbia surveyed 352 professionals and representatives of 33 city and state organisations relevant to GI. The aim was to identify barriers and drivers within a broad conceptual framework in the following areas: (1) formulating a legal framework for GI; (2) regulating the conservation of existing GI elements; (3) improving GI planning regulation; (4) improving regulation in the fields of design and construction; (5) enhancing regulation for green infrastructure maintenance; (6) regulating GI management; and (7) enhancing awareness, knowledge, and information dissemination about GI.

Drawing from both theoretical foundations and practical applications, green infrastructure (GI) can serve as the missing link between people, nature, and the built environment. It offers a cost-effective and efficient solution for addressing multiple challenges simultaneously [36], achieved through the integration of interdisciplinary factors such as pollution mitigation, habitat and biodiversity conservation, improvement in the quality of life, provision of food and energy, facilitation of recreation, and enhancement of landscape values.

2. Method

To conceptualise the regulation of green infrastructure (RGI) in Serbia, the viewpoints of professionals directly or indirectly involved in green infrastructure (GI) were explored. An examination and analysis of the scientific literature facilitated the thematic mapping and categorisation of these viewpoints [37] to facilitate the selection and direction of the survey [38]. The selection criteria for respondents were based on their understanding and expertise related to assessment tools and other evaluation methodologies, as well as their professional interest in GI development. Therefore, the study did not encompass the viewpoints of citizens, as knowledge and experience were considered as being necessary for the systemic approach to GI regulation. Questionnaires were distributed among landscape architects, urban planners, spatial planners, architects, civil engineers, forestry engineers, horticulture engineers, and ecologists, as well as professionals in law, culture, tourism, environmental and nature protection, transportation, technical infrastructure, economics, and others employed in institutions with experience in GI.

Professionals employed in urban secretariats (departments for environmental protection, urban planning and construction, communal and residential affairs, culture, economy, transportation, etc.); government institutions (construction, transportation, infrastructure, environmental protection, etc.); state and city public enterprises engaged in the planning, management, and maintenance of green infrastructure elements (public green spaces, forests, watercourses, etc.); as well as non-governmental organisations focused on enhancing urban quality were surveyed.

The total number of professionals surveyed amounted to 352. The study made use of data collected from surveys conducted between 2018 and 2023 (Table 1).

Table 1. Summary of surveys conducted among professionals from 2018 to 2023.

Survey	Number of Participants	Participant Type	Number of Questions in the Questionnaire
Legal Regulation as a Mechanism for Green Space Sustainability (2018)	47	Individuals—professionals	31
Green Infrastructure in Serbia (2019)	167	Individuals—professionals	24
Green Infrastructure Strategy (2020)	96	Individuals—professionals	8
Green Infrastructure Strategy of Belgrade (2023)	42	Representatives of 32 city and state organisations relevant to GI	45

Before conducting the survey in 2018, pilot interviews were conducted with experts from national professional associations, with the support of the Ministry of Environmental Protection of the Republic of Serbia. The aim was to define the questions to be answered in a larger sample. Pilot interviews, serving as trial surveys in this research, were conducted with a sample of 10 respondents to identify and rectify any errors before broader data collection. Additionally, they helped to identify any ambiguities enabling surveyors to seek clarification from respondents [39]. The questionnaires were structured to encompass various types of questions, including closed-ended questions with a predefined set of responses, open-ended questions, and open-ended questions allowing for additional responses. Questions were classified based on different aspects related to which professionals' attitudes were assessed. During a workshop held on 31 October 2018, participants responded to questions related to the preservation of existing greenery and green spaces (9 questions); planning, designing, and constructing new green spaces (10 questions); and using and maintaining green spaces (12 questions). The questions were open-ended to avoid bias in the research (Supplementary Material S1).

The responses partly confirmed the emphasis on problems that had already been identified as being significant, but there were also entirely new topics based on which the questionnaire (Supplementary Material S2) was compiled for the subsequent year of the research. This questionnaire included both closed- and open-ended questions.

An electronic survey was conducted in September and October 2019, containing the following question groups: general information about the respondents (4 questions); understanding of the concept of GI (2 questions); assessment of the state of GI in Serbia (12 questions); suggestions for improving the state (5 questions); and additional comments (open-ended responses).

In the third year of the research, based on the surveys conducted in 2018 and 2019, a questionnaire was structured comprising both closed- and open-ended questions (Supplementary Material S3). In October 2020, an electronic survey was conducted on the possibilities for implementing the European Green Infrastructure Strategy in Serbia. The questionnaire consisted of general information about the respondents (2 questions) and questions about the European GI Strategy and its implementation in Serbia (5 questions). With knowledge obtained from literature reviews and three conducted surveys, a questionnaire (Supplementary Material S4) with open-ended questions was structured in 2023. The qualitative research method of "in-depth" interviews was utilised, where the interviewer engaged respondents in dialogue and posed additional questions to clarify their responses. This survey was implemented as a part of the "Belgrade Green Infrastructure Strategy" project, and a survey was conducted with questions related to the legal framework of

GI (4 questions); organisation, management, and procedures in the context of GI (9 questions); preservation of existing GI elements (3 questions); GI planning (11 questions); GI design and construction (8 questions); GI maintenance (4 questions); and awareness and knowledge of GI (6 questions).

For the purpose of this study, all the questionnaires were transcribed and coded, with repetitions and digressions omitted beforehand. The most frequent and relevant responses were utilised and systematised into areas that could be parts of GI regulation. The number of responses to individual questions varies because participants did not respond to every question that was posed.

The surveys were analysed using text analysis techniques [40]. Microsoft Excel 2016 (KB5002454) 64 was used for creating graphical illustrations.

3. Results

3.1. Legal Regulation as a Mechanism for Green Space Sustainability

In the survey on legal regulation as a mechanism for the sustainability of green spaces (2018), participants were presented with a total of 31 questions. From the first group focusing on the "Preservation of Existing Greenery and Green Spaces", a total of 9 questions were aimed at gathering ideas to be incorporated into regulations to preserve existing green spaces as being the most developed and, therefore, most valuable for the environment. The key responses are presented in Table 2.

Table 2. Selected suggestions from respondents for the preservation of existing greenery and green spaces.

Preservation of Existing Greenery and Green Spaces
➢ Green spaces should be a public good (public interest).
➢ A new law or sublegal act should be developed to regulate greenery.
➢ Existing green spaces should benefit from a certain level of protection.
➢ There should be a cadastre of greenery as a part of the spatial database.
➢ The conversion of green areas should be prohibited.
➢ Mandatory fieldwork should be introduced for planners and designers, and the existing one should be valorised.
➢ Participation of landscape architects in planning commissions should be made mandatory.
➢ Penalties and compensation for destroyed greenery should be introduced.
➢ Tax incentives for investors to protect existing greenery should be provided.
➢ Plans and projects should be adapted to existing vegetation.
➢ Technical standards for protecting existing greenery during construction should be developed.
➢ Preference should be given to existing trees over installations.

The second group of questions, totalling 10, focused on "Planning, Designing, and Building New Green Spaces". The questions aimed to generate ideas for improving regulations in the spatial planning process for the more efficient creation of new green spaces. The key responses are presented in Table 3.

The third group of questions, totalling 12, focused on the "Utilisation and Maintenance of Green Spaces". This group of questions aimed to propose measures that would standardise construction works, the initial maintenance after the establishment of green spaces, and mandatory maintenance and offer solutions to ensure the issues of green space survival. The most valuable suggestions are presented in Table 4.

Table 3. Selected suggestions from respondents for planning, designing, and building new green spaces.

Planning, Designing, and Building New Green Spaces
➢ Defining a protocol for green space planning;
➢ Incorporating the protection of existing greenery within the planning framework;
➢ Introducing new parameters for evaluating greenery, such as ambience, cultural values, and ecosystem services;
➢ Introducing standards to the planning process;
➢ Planning structured greenery (at all levels, not just lawns);
➢ Introducing subsidies for new green spaces;
➢ Ensuring equal treatment for biotechnical objects as for buildings;
➢ Planning and designing in line with contemporary needs, such as water conservation, soil porosity preservation, connectivity, green roofs, green facades, and using plants resilient to altered microclimates;
➢ Planning the unity of blue–green corridors;
➢ Protecting greenery on private property through planning;
➢ Implementing clearer control mechanisms.

Table 4. Selected suggestions from respondents for the utilisation and maintenance of green spaces.

Utilisation and Maintenance of Green Spaces
➢ Developing standards for design and construction works;
➢ Standardising descriptions and norms of works;
➢ Creating regulations defining initial maintenance works after the establishment of green spaces, specifying types of works, warranties, calculation methods, etc.;
➢ Providing conditions to increase the self-sustainability of green spaces;
➢ Defining mandatory maintenance requirements;
➢ Inciting the maintenance of private spaces and offering them expert maintenance guidance;
➢ Including a professional, such as a landscape architect, as a member of the urban planning team;
➢ Establishing a centre for processing plant waste;
➢ Introducing irrigation systems, combined with the use of atmospheric water;
➢ Preventing encroachment on green spaces;
➢ Prohibiting the unplanned planting of Christmas trees.

3.2. Green Infrastructure in Serbia

In the second, electronic survey (2019), general information about the respondents covered questions regarding their profession, area of work, level of education, work experience, and gender (Figure S1 in the Supplementary Material).

This group of questions concerning “Understanding the Concept and Importance of GI” aimed to examine experts’ attitudes regarding the importance and impacts of various elements of GI. In response to the question, “Evaluate to what extent the following terms relate to the concept of ‘green infrastructure’”, nine options were provided to discover which elements professionals considered to be the most valuable in GI within urban environments and surroundings. The responses are presented in Figure 2.

Of the nine provided terms, all the elements of green infrastructure were rated as being significant. However, experts considered parks, tree rows, and urban fringe forests to be the most important elements of green infrastructure. The importance of roadways, zones of individual housing, and agricultural land was rated the lowest.

Responses to the question “Evaluate the importance of green infrastructure for the quality of life in urban environments”. are presented in Figure 3.

Of the 11 provided responses, experts assessed that GI was very significant for all 11 contributions but mostly for its impacts on the climate, air quality, biodiversity, and ambience. Respondents less commonly perceived the importance of GI for residents’ education and soil quality.

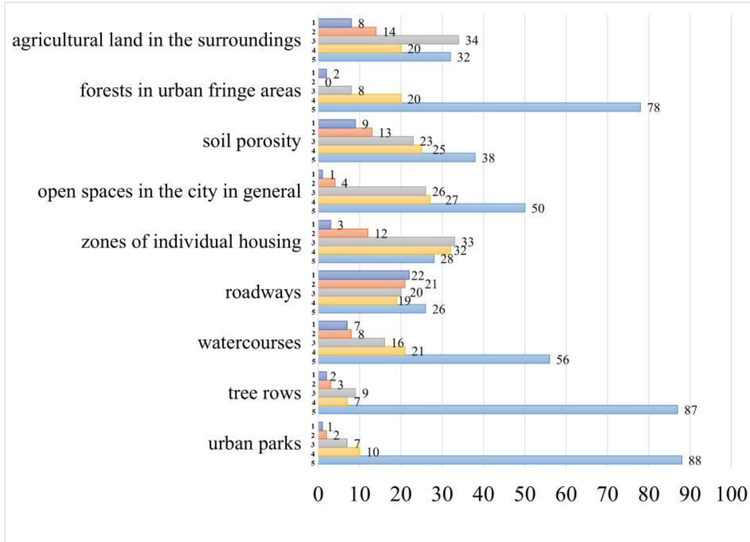

Figure 2. Summarised responses to the question "Evaluate to what extent the following terms relate to the concept of 'Green Infrastructure'".

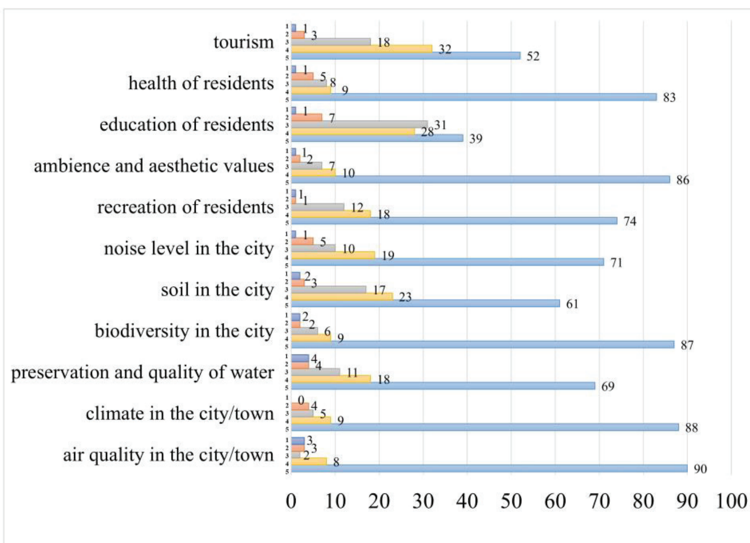

Figure 3. Summarised responses to the question "Evaluate the importance of green infrastructure".

Within the group of questions concerning the "Assessment of the Current Situation in Serbian Cities", respondents were tasked with evaluating how GI is treated in practice in Serbia based on 12 indicators. In response to the question, "Based on your own experience and observations in your environment, assess the current state of the relationship to green infrastructure, considering the listed evaluation elements", they were offered 12 elements to assess the relationship to GI. These elements were aimed to reveal the general relationship to green spaces, e.g., whether experts check the situation in the field, whether documents contain all the necessary information, whether plans include conditions for nature protection, whether responsibilities are defined, and what is the position of experts. Elements were rated from poor treatment (rating 1) to the best treatment (rating 5) and are presented in Figure 4.

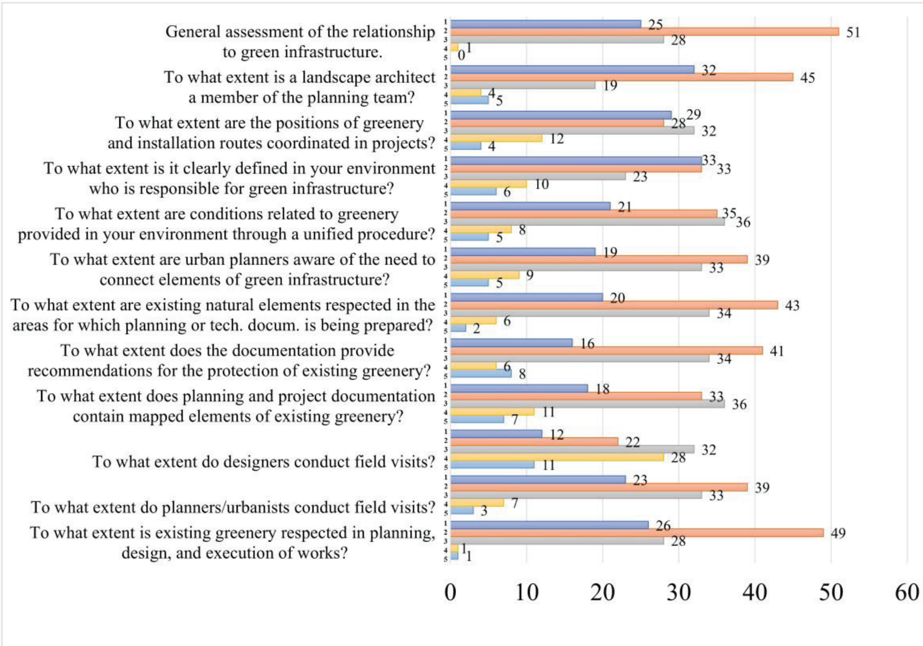

Figure 4. Summarised responses to the question "Evaluate the relationship to green infrastructure in Serbia".

Ratings for all the elements fell between 2 and 3, indicating that surveyed experts assessed the treatment of GI as being very unfavourable. The lowest-rated aspect referred to the respect for existing greenery during planning, design, and construction. This rating of the relationship to GI was unfavourable.

In response to open-ended questions, various measures were proposed to enhance the development of GI in Serbian cities through legislative regulation, rules, organisation, standards, etc.

In response to the question "Suggest measures for preserving existing elements of green infrastructure", the following measures emphasising the preservation of existing elements of GI were underscored: drafting a specific law, prescribing the prohibition of tree destruction and imposing penalties for offenders, broadening the responsibilities of expert commissions for tree assessment, mapping and documenting the existing condition, creating a cadastre, education and awareness raising, defining a responsible manager (director), and declaring greenery as public property.

Regarding the development of the cadastre, the majority of the respondents, when asked to "Suggest measures for implementing the green infrastructure cadastre", proposed the following: allocation of financial resources from the state and municipalities, engagement of experts for cadastre-related tasks, organising training for professionals and municipal authorities, and digitalisation in the field of green infrastructure and the development of a GIS (geographic information system) for these purposes.

In response to the question "Propose measures in the field of planning aimed at improving and developing green infrastructure in the cities of Serbia for the needs of GI planning", the following answers were highlighted: the establishment of a cadastre as a basis for planning, the development of a preliminary strategy, team collaboration among various experts, mandatory involvement of landscape architects in plan development, the development of regulations, the establishment of planning standards and norms, and the implementation of special measures for preserving green corridors.

In the sphere of the design, in response to the question "Suggest measures for improving green infrastructure", the following proposals were made: introducing an obligation to carry out projects, mandating the preparation of a bioecological plan and an assessment of the existing state, clarifying the conditions of urban plans, formulating new regulations, developing standards in design, and utilising native species.

Answers to the question of how to organise or manage green infrastructure in Serbian cities demonstrate great diversity and opposition among experts' opinions. It was proposed that organisations, such as public utility companies, public urban planning enterprises, city secretariats, city landscape architects, nature conservation institutes, municipal administrations in collaboration with municipal police, and even private organisations, should take over the management of GI. However, there were opposing proposals suggesting that public utility or urban planning enterprises should not be managers because of conflicts of interest. Instead, these respondents proposed the establishment of a special organisation—a directorate for GI.

Some of the surveyed professionals had additional comments. In these additional, as well as other written, responses, the following points were emphasised: the needs to organise professional conferences; raise awareness among residents; ensure greater involvement of landscape architects in spatial planning; allocate more funds; adopt strategies, laws, rules, and standards; and combat corruption. There was also a highlighted need to abolish the monopoly of urban public utility companies for greenery to create healthier competition and higher-quality and more-affordable services.

3.3. Implementation of Green Infrastructure Strategy

In the third, electronic survey (2020), general data on the respondents included questions regarding their gender, level of education, and field of professional engagement (Figure S2 in the Supplementary Material).

The second set of questions aimed to examine the opinions of the professional community regarding the European Green Infrastructure Strategy, its significance, the need for it, and the potential opportunities for its application in domestic regulations. The questions and answers are presented in Figure 5.

In 2020, half of the surveyed professionals were only partially familiar with the European GI Strategy (2013). Professionals believed that GI should definitely be established in the legislation of the Republic of Serbia, either through a new law or by inclusion in existing ones. The most prevalent opinion among surveyed experts was that GI should be integrated within the framework of all the relevant laws. The majority of the respondents believed that a potential GI Strategy in Serbia should be defined at both the national and local levels. Over 80% of the surveyed professionals thought that GI should be planned synchronously both as a separate theme and within sectoral themes.

Considering the state of practice in Serbia and the year of conducting the survey (2020), even the partial familiarity of the professional community with the existence of the European GI strategy can be considered as being acceptable awareness. Over time, this awareness undoubtedly increases. The multidisciplinary perspective of all the professionals on the GI issue is particularly valuable. This survey shows the strong determination of the respondents that it is necessary to legislate in the area of GI. In this regard, it can be concluded that working on a systematic approach to regulation is a logical step towards forming a regulatory framework for GI.

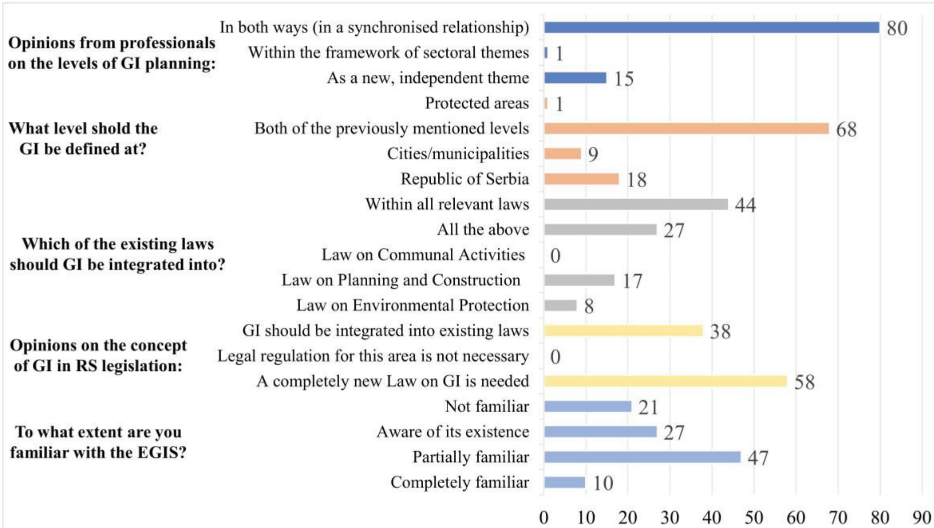

Figure 5. Summarised responses to the set of questions aimed to examine the opinions of the professional community regarding the European Green Infrastructure Strategy.

3.4. Green Infrastructure Strategy of Belgrade

After identifying and systematising issues, the development of the Green Infrastructure Strategy of Belgrade (2023) included 820 ideas submitted as proposals. The proposals were classified as responses to the registered problems. The highest number of proposed ideas fell within the Planning of Green Infrastructure (166), while the least was related to the Preservation of Existing GI Elements (64). Based on the questionnaire from the Belgrade GI Strategy survey, problems were systematised and classified into 8 groups, and the most frequent responses were singled out (Table 5).

Table 5. Systematisation of issues and most frequent responses.

1. General issues regarding GI:
➢ The lack of a systematic approach towards GI; ➢ Unequal treatment of GI compared to other urban structures; ➢ Failure to recognise the link between GI and ecosystem services; ➢ Insufficient recognition and application of GI in climate change adaptation; ➢ The lack of knowledge and awareness about GI as a public interest and general natural and cultural asset.
2. Legal framework issues of GI:
➢ The absence of a legal framework in the field of GI at all levels; ➢ Inadequate implementation of existing legal and planning regulations in areas related to GI elements; ➢ Inadequate prescribing of sanctions in the field of GI; ➢ Inadequate inspection control.
3. Issues of organisation, management, and procedures in the context of GI:
➢ The existing organisational structure is insufficient for the development of GI; ➢ Poor intersectoral collaboration; ➢ Incomplete and imprecise conditions of public authorities for planning and developing technical documentation; ➢ The lack of incentive measures for the development of GI; ➢ Jurisdictional issues over GI elements; ➢ Owners and/or users of certain GI elements lack the capacity for their maintenance and improvement (schools, hospitals, residential blocks, etc.);

Table 5. *Cont.*

➢ The absence of models enabling the maintenance of public GI elements by the private sector; ➢ Inadequate collaboration established between citizens and public authorities; ➢ "Shifting responsibilities" to managers who lack the capacity to solve specific problems (e.g., illegal construction on GI surfaces).
4. Issues for preserving existing GI elements:
➢ Degradation and usurpation of GI elements (often viewed as spatial resources and space available for construction); ➢ Vulnerability of GI elements not formally protected but valuable in terms of biodiversity conservation, cultural heritage, and/or spatial identity; ➢ Insufficient recognition of GI elements in private ownership.
5. Problems for GI planning:
➢ Insufficient number and surface area of GI elements, poor spatial distribution, and lack of connectivity; ➢ Inadequate space reserved for new GI elements during the planning process; ➢ Ignoring the potential for addressing environmental issues resulting from climate change through GI planning; ➢ The lack of a multidisciplinary approach for planning, in which spaces of different purposes are planned integrally with GI elements; ➢ Inconsistent regulative norms for preserving existing and constructing new GI elements; ➢ The absence of a planning approach that improves conditions and addresses problems by respecting ecosystem services; ➢ Failure to conduct evaluations for planning solutions through levels of ecosystem service provision; ➢ Inconsistent typology of GI within the city territory; ➢ Incomplete geographic information system (GIS) for GI; ➢ A tendency to plan public GI not accessible to everyone; ➢ Unresolved property–legal relationships affecting existing and planned GI elements.
6. Issues with designing and constructing GI:
➢ Designing and building without assessing and integrating existing GI elements into the solution; ➢ Underutilisation of the potential for forming GI structures, such as roofs, walls, and facades, of public and private buildings; ➢ Conflict between technical infrastructures and GI; ➢ Neglecting the multifunctional (environmental and aesthetic) significance of GI elements during GI feature design; ➢ Overlooking the multifunctionality of GI elements during feature design (impacts on its aesthetics, microclimate influence, noise reduction, etc.); ➢ Inadequate equipment for public green infrastructure elements; ➢ The lack of a wide range of plant materials in the domestic market, especially those suitable for extreme conditions in urban environments and changing climate conditions; ➢ The absence of an approach designed to enhance biodiversity in project solutions; ➢ The lack of data on GI elements within location information (construction possibilities and restrictions).
7. Maintenance issues of GI:
➢ Inadequate financial resources for the regular maintenance of GI; ➢ Insufficient staffing capacities; ➢ Inadequate maintenance of green areas adjacent to multi-family (collective) residential buildings; ➢ The presence of invasive species in GI elements and the lack of a systemic solution for their permanent elimination.
8. Awareness and knowledge about GI:
➢ Insufficient education of stakeholders in the decision-making, planning, and design processes regarding the significance of GI; ➢ Inadequate understanding of the importance of the multifunctionality of GI and its synergistic effects with other activities; ➢ Limited media promotion of the importance of GI; ➢ Limited knowledge about the use of available and innovative solutions; ➢ Investors do not recognise the potential for investing in GI; ➢ Insufficient involvement of citizens in the GI planning and design process.

4. Discussion

Structured and semi-structured questionnaires were applied to identify barriers and drivers in conceptualising elements of green infrastructure regulation for the needs of local and regional urban development. The importance for researching these attitudes lies in the following characteristics of professionals: theoretical knowledge of the concept of green infrastructure; practical experience in working with green infrastructure; experience gained in organisations and institutions responsible for planning, designing, constructing, maintaining, or managing green infrastructure; and practical experience in procedures that are important for implementing the concept of green infrastructure.

By analysing and coding responses, seven areas were identified in which key barriers and drivers were registered (Figure 6a–g):

(1) formation of the legal framework for green infrastructure;
(2) regulation of the preservation of existing green infrastructure elements;
(3) improvement of the regulation for green infrastructure planning;
(4) improvement of the regulation in the field of design and construction;
(5) improvement of the regulation for the maintenance of green infrastructure;
(6) regulation of green infrastructure management;
(7) awareness, knowledge, and information about green infrastructure.

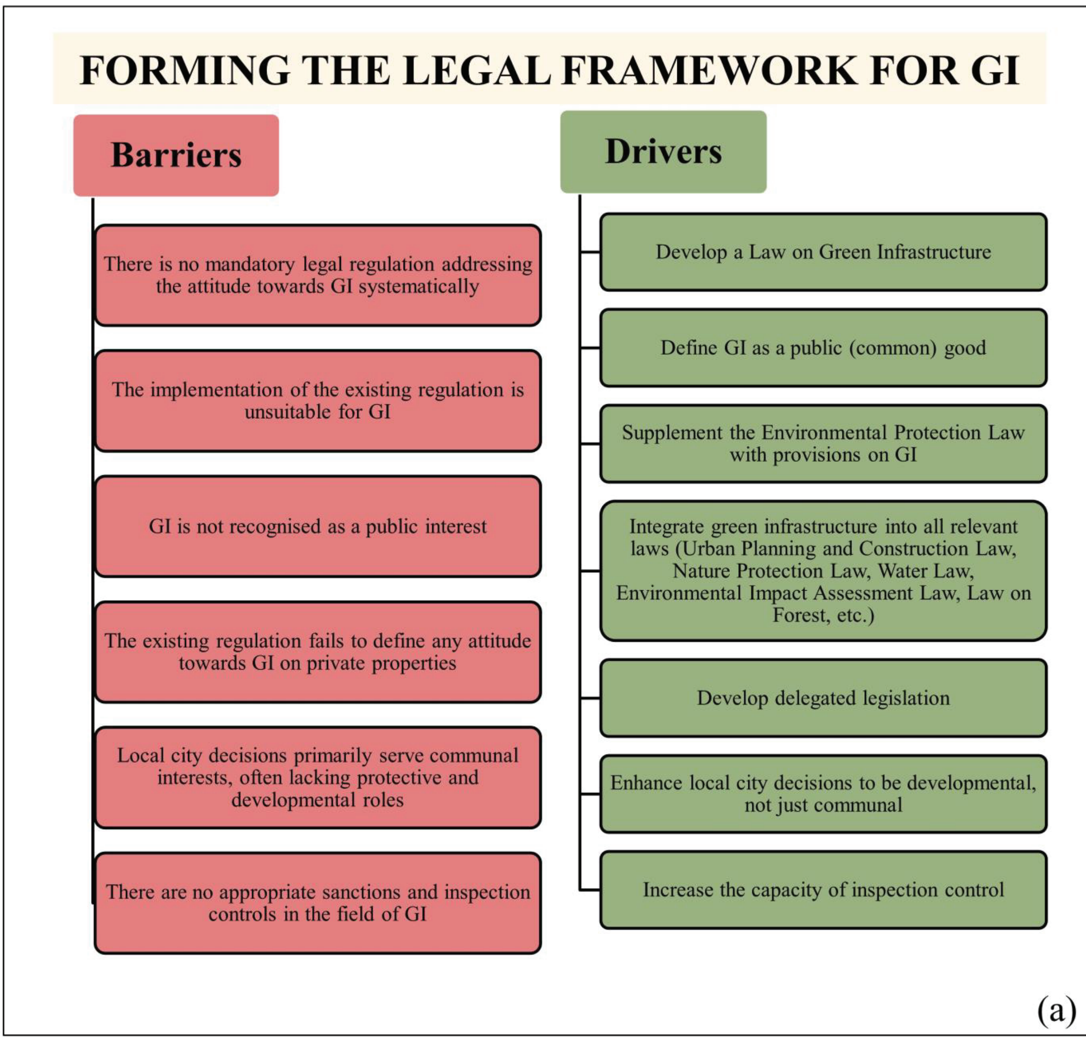

Figure 6. *Cont.*

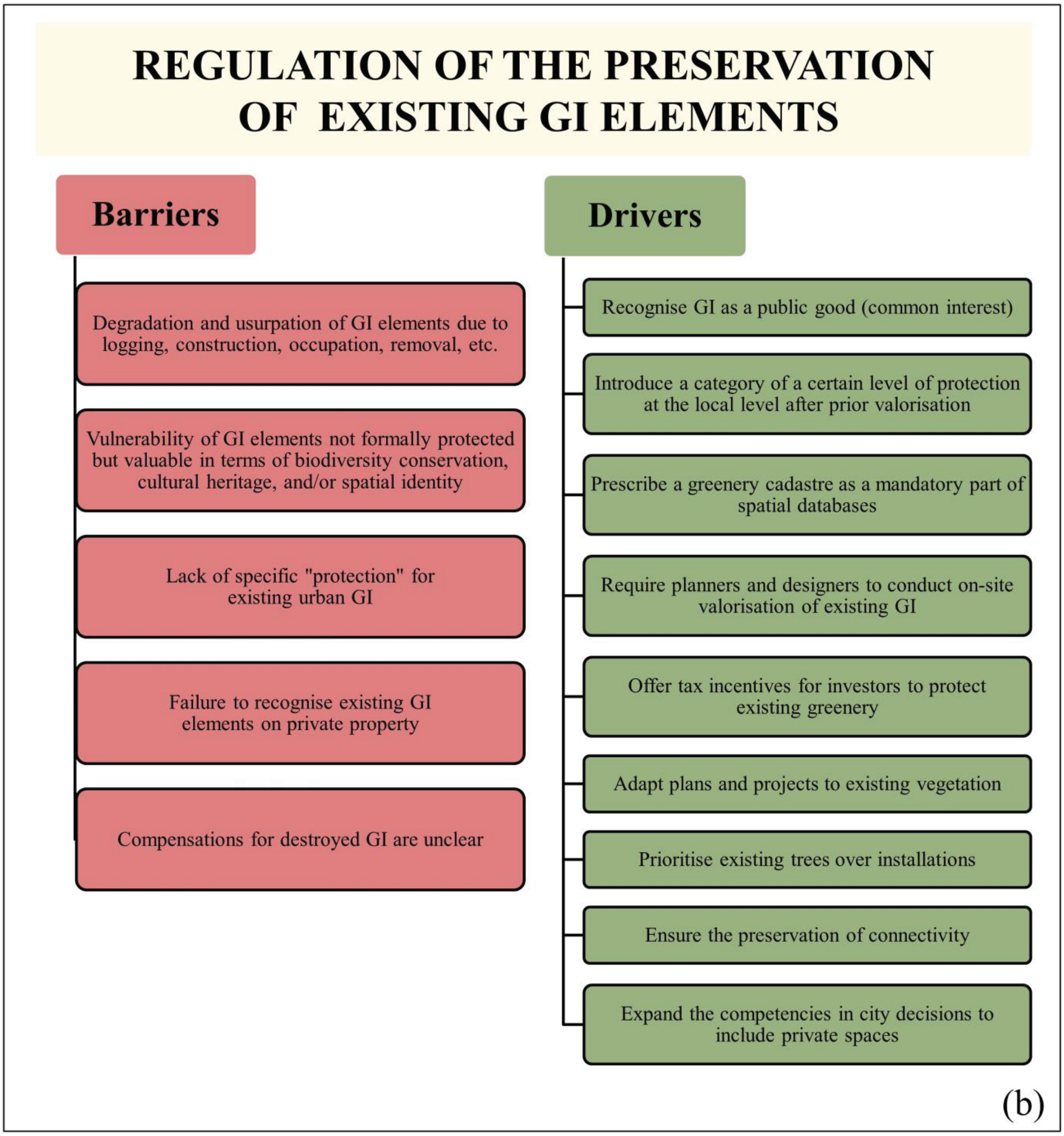

Figure 6. *Cont.*

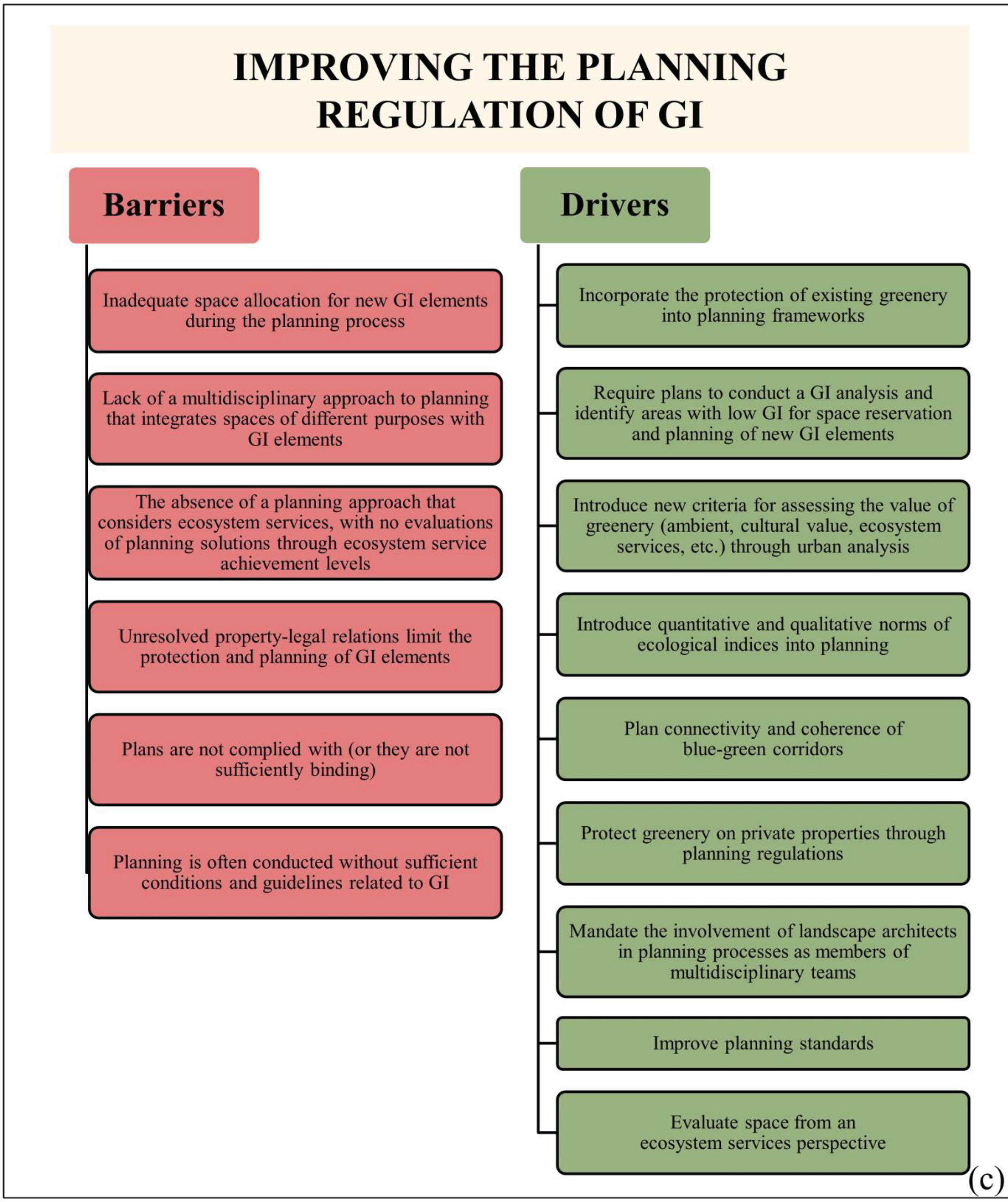

Figure 6. *Cont.*

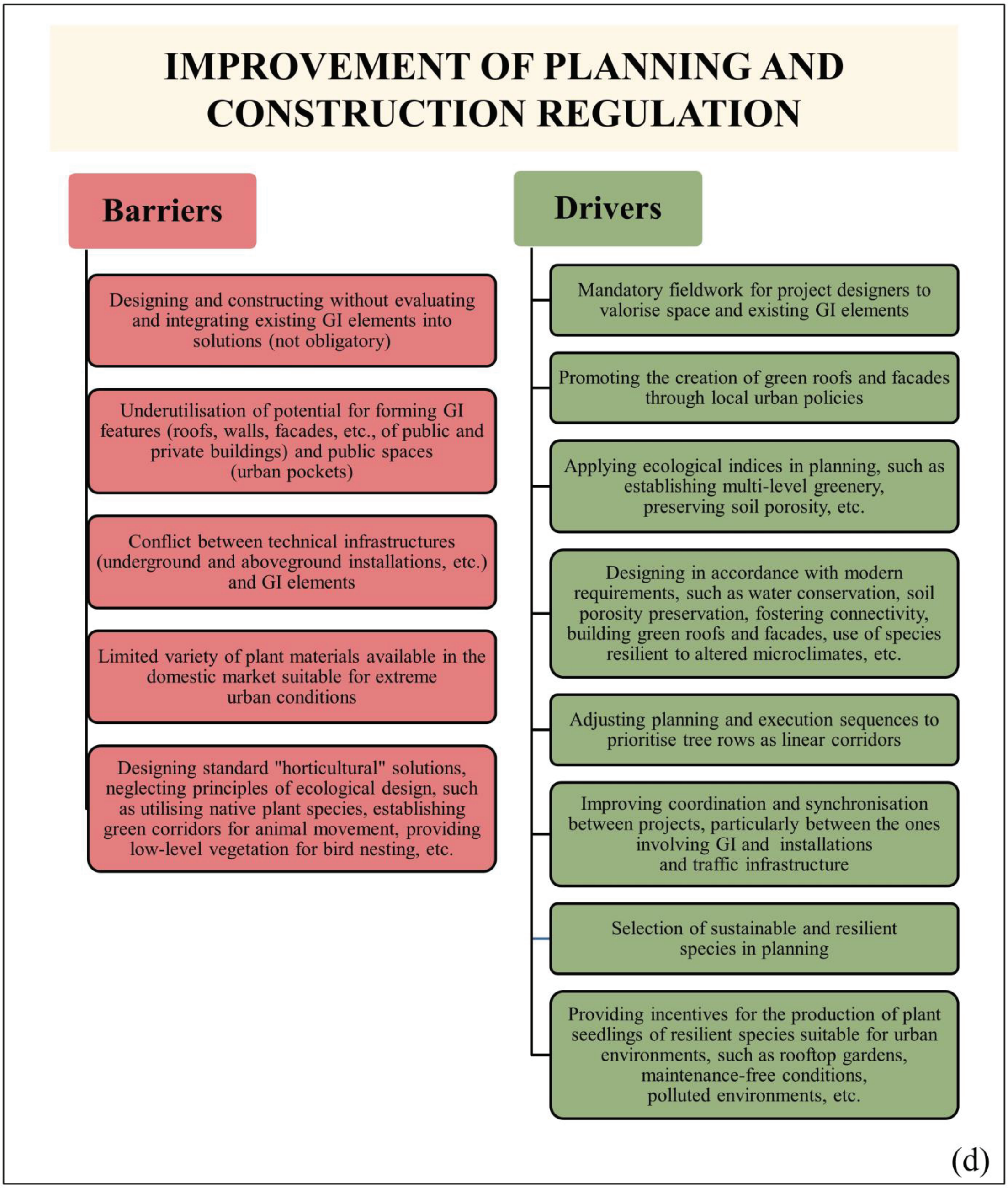

Figure 6. *Cont.*

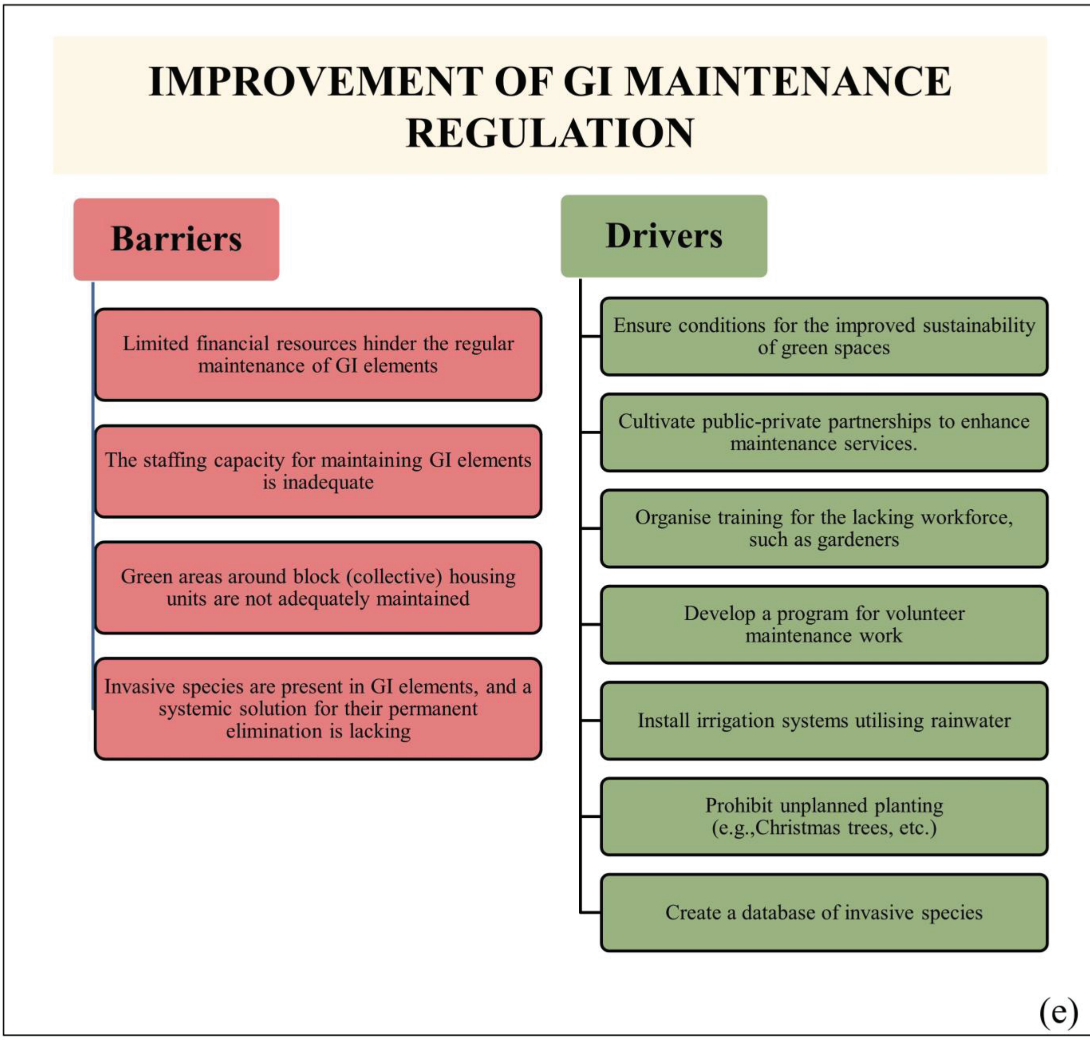

Figure 6. *Cont.*

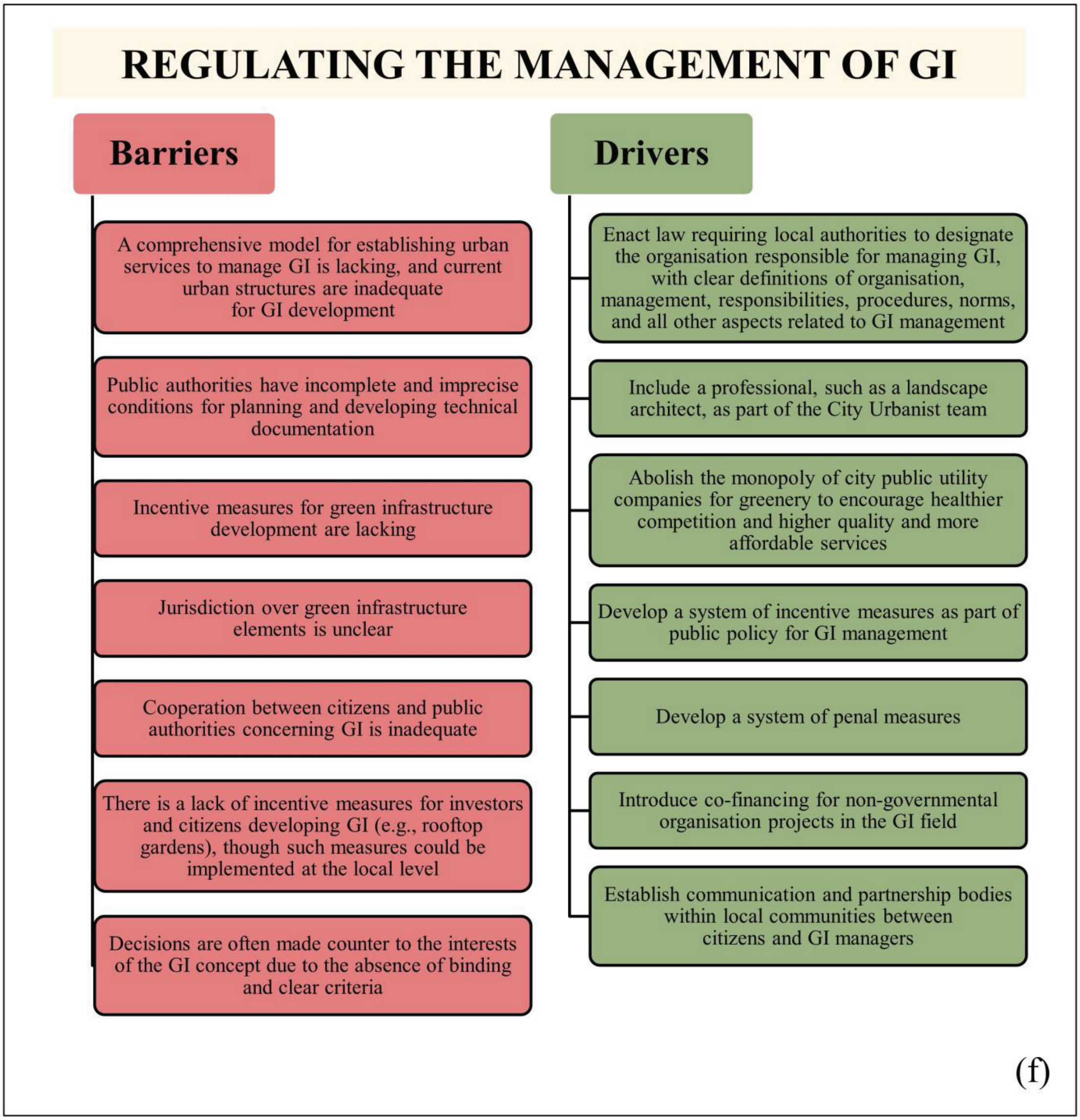

Figure 6. *Cont.*

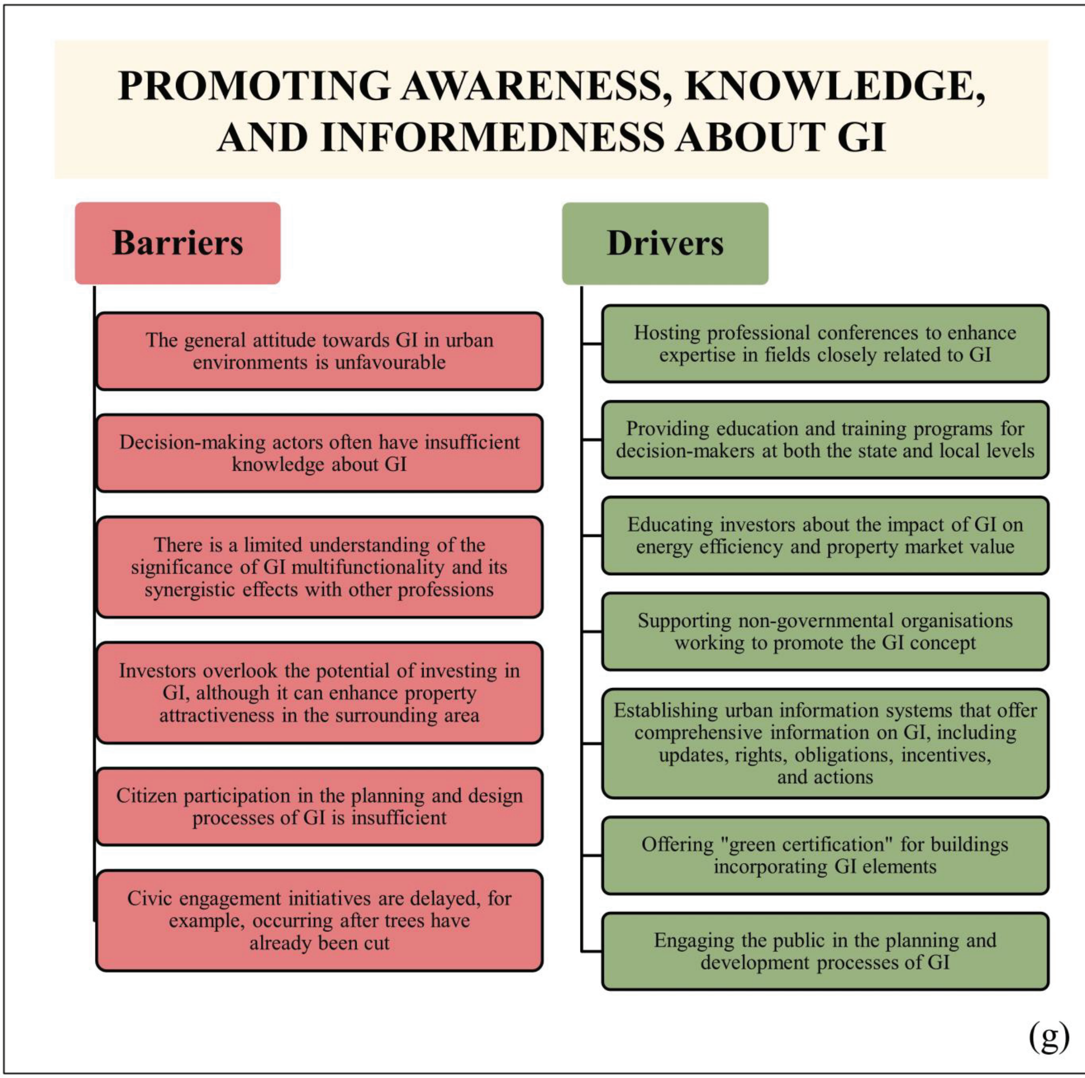

Figure 6. Systematised attitudes of professionals: (**a**) legal framework of GI, (**b**) regulation of preservation of existing GI elements, (**c**) planning of GI, (**d**) regulation of design and construction, (**e**) regulation of GI maintenance, (**f**) management of GI, and (**g**) ways to enhance awareness and understanding of GI.

The development of green urban infrastructure and its management in urban centres are facilitated and strengthened by policies, strategies, and other legal instruments. At the national level, several documents have been developed in recent years; however, they have little connection with the development and management of green urban infrastructure. Additionally, experts, government officials, and the public do not interpret these documents in the same way, which aligns with the findings of Keita and Kourouma [41]. Urban GI is a strategically developed network of green spaces that can improve the quality of the environment and provide significant economic benefits [17]. It is in line with the Sustainable Development Goal [42], which calls for resilient, safe, sustainable, and inclusive cities. However, the primary barrier for creating and managing urban green infrastructure is the lack of commitment, competent workforces, financing, and public participation. This study aims to identify existing research and policy gaps and complement the limited empirical literature on RGI. The identified barriers and drivers (Figure 6a–g) serve as a database for institutions involved in the development and management of GI, including legislators, planners, managers, and other interested groups.

Our five-year research on the segment concerning the formation of the legal framework for green infrastructure (Figure 6a) aligns with findings [43,44] indicating that national organisations should take the lead in finding the most suitable solution, within the national context, to integrate appropriate instruments into the legal framework. Furthermore, it is crucial to encourage national municipalities to continue their efforts towards the development and implementation of indicators, as recommended by Bläser et al. [45] for Germany and Antoszewski et al. [46] for Poland. Presently, building standards do not enforce strict ecological solutions; instead, laws and regulations are yet to adopt a purposefully oriented, holistic, and interdisciplinary approach to facilitate legal evolution contributing to the progress of green infrastructure [47].

The preservation of existing green infrastructure (GI) elements (Figure 6b) requires an assessment of the effectiveness of ecological safety patterns and green space systems in urban areas, as well as the efficiency of the GI network [48], alongside an evaluation of current conditions for implementation. Our research highlights historical and cultural landscape features, as well as linear elements that can enhance connectivity within and to urban spaces, promoting more sustainable GI, as also observed by [49] for Ankara. Wei et al. [15] stress the importance for identifying existing structural GI elements and suggest incorporating morphological variables, such as “connectivity value”, “degree of integration”, and “value of understanding”, which serve as quantitative parameters of spatial structure. These proposals closely align with the findings of our research regarding the regulation of existing GI elements.

Based on the identified drivers in our study, it is evident that enhancing GI planning regulations (Figure 6c) requires the implementation of strategies as tools for nurturing and revitalising the quality of urban life. Given its multifunctional impact, GI as a network generates greater benefits than the sum of its individual parts, all of which contribute to ecological, social, and economic advantages [50]. However, the planning and execution of the GI concept in urban environments necessitate the collaboration of all the relevant stakeholders towards supporting long-term objectives. This can be achieved through strategic framing and the delineation of operationalised tasks for all levels of governance in a collaborative process [51,52]. Additionally, it is essential to disseminate knowledge about ecosystem services to stakeholders, along with adopting new planning approaches that consider the qualitative aspect of public action based on performance standards, aiming to provide multiple benefits in terms of regulation, support, and cultural services [53]. In light of the current dynamic global landscape, GI is gaining prominence in planning policies, primarily because of its ecological, economic, and social components, which contribute to the sustainable and resilient planning and design of smart cities and spaces [51,54]. The issue of GI is contextualised within the conceptual frameworks of sustainability and resilience, which are described through an examination of their shared characteristics and disparities, with a specific emphasis on planning elements [55].

The rationale for enhancing the regulatory framework for designing and constructing sustainable, resilient, and smart cities and GI networks (Figure 6d) stems from the 2030 Agenda for Sustainable Development and current European strategies: the EU GI Strategy, EU Climate Adaptation Strategy, EU Biodiversity Strategy for 2030, and other strategic documents [56–58], which recognise GI and nature-based solutions as being critical approaches and tools for design and implementation in urban environments and landscapes. Our research identifies drivers for GI design and construction at both holistic and specific levels. Specifically, the experiences and empirical findings of national professionals underscore the importance of public involvement and engagement, as well as the wide array of ecosystem services provided by GI and its elements, including some potential ecosystem disservices.

Our findings in this regard partially align with results cited by Hanna and Comín [17], Tzoulas et al. [59], the Forestry Commission [60], Toth and Timpe [61], Williams [62], and Pochodyła et al. [63].

To enhance the maintenance regulation for GI (Figure 6e), several prior studies have underscored the significance and benefits achievable through GI maintenance [64–67]. From the viewpoint of national professionals, the maintenance requirements for various types of GI vary considerably depending on their specific type and design, requiring not only adequate financial resources but also a thorough understanding of maintenance practices to ensure effective upkeep. This encompasses responsibility and maintenance planning through monitoring and comprehensive documentation, training and education on GI maintenance, mechanisms for compliance, and ensuring dedicated funding sources. In addition to pursuing the primary goals of GI maintenance, there are multiple other objectives associated with the optimisation process. When optimising GI maintenance, all these factors must be taken into account to ensure the optimal maintenance with the maximum benefits and minimal costs. This study emphasises the importance for systematically optimising GI maintenance through the engagement of multidisciplinary stakeholders, similar to the approach by Hansen and Pauleit [68].

Based on research on the regulation of GI management (Figure 6f), it has been established that the current GI management models in Serbia are insufficient for addressing contemporary issues related to sustainable development and GI protection, a situation similar to that in Italy [69]. Throughout our five-year study, professionals have underscored the importance for adopting new approaches that integrate the benefits of ecosystem services provided by GI into traditional management frameworks, thereby achieving a higher level of ecological performance essential for enhancing quality of life. Both in Serbia and Italy, there are no mandatory planning tools for the design and management of GI, and they are now a part of traditional land use plans [69]. Moreover, the lack of financial resources allocated towards the development of "green standards" presents a challenge for the majority of the public administrations in Serbia as well as in other countries [69–71]. Therefore, it is proposed to abolish the monopolies held by public utility companies for green spaces to foster competition, deliver higher-quality services at more-affordable rates, and establish a cohesive management strategy.

The perspectives of professionals regarding the enhancement of awareness, knowledge, and information about GI (Figure 6g) are consistent not only with each other but also with the findings of Inzunza-Acedo [72], asserting that despite the prevailing influence of social media globally, there is still a need for arranging professional conferences and educational programs for decision-makers, investors, and the general public. A particular emphasis is placed on promoting the GI concept across social media platforms. Our research findings partially align with the study conducted by Metastasio et al. [73], which explored the role of social media and the outcomes derived from posts shared on two widely used platforms (Facebook and TikTok) during 2022 and 2023. Their results validate the significance of social media as indicators of current trends in the evolution of information dissemination.

This study investigates variable policies and legal frameworks for green infrastructure development in Serbia from the perspective of urban development, aiming to enhance the contributions of local experts rather than consulting foreign experts who may not be familiar with urban landscapes. The expressed views of these professionals, systematically categorised into appropriate groups, provide a valuable and rich source of information about barriers existing in Serbia's practice as well as initiatives to be applied in future GI regulation. The obtained results partially align with those obtained by Pakzad and Osmond [74], who utilised conceptual foundations to establish a framework for assessing the sustainability of GI elements. Their framework consists of 30 indicators classified into four categories, including ecological, health, socio-cultural, and economic indicators.

5. Conclusions

This paper thoroughly examines the challenges facing green infrastructure (GI) in both policy and practice, identifying barriers and drivers crucial for a systemic approach to GI regulation. By integrating the experiences and views of professionals, tools for assessing existing GI policies at the national level were identified. These selected tools can be applied across various dimensions in the revision of existing laws and planning documents or the development of new strategies.

The findings drawn from the research enable the identification of barriers and drivers aimed at integrating processes and enhancing the utilisation and adoption of natural solutions for many key challenges in urban development, which link GI performance with ecosystem services, health, and human well-being. The systemic approach to GI regulation in Serbia is still in its infancy and is not fully accepted by decision-makers in a proper manner. However, the results of this research suggest that professionals, government agencies, and academic researchers should consider and propose methods to establish GI regulation and evaluate its performance. Furthermore, this research has demonstrated that over several years (2018–2023), there have been progress and increased understanding among professionals regarding the need to enhance the concept of green infrastructure, indicating a higher level of comprehension of the issues. The conceptualisation of GI regulatory elements provides a purposeful cognitive platform for establishing a composite model based on tangible indicators to evaluate GI performance.

After five years of thorough research, we conclude that this study surpasses national significance as GIS planning and design manifest in various dimensions and environments as strategic concepts integrated into international policies of the world and the EU as well as regional, national, and local concepts. This study introduces a novel framework (concept) compared to previous research endeavours. This framework, based on professionals' perspectives, comprises seven key indicator areas: formulating a legal framework for GI, regulating the conservation of existing GI elements, improving GI planning regulation, improving regulation in the fields of design and construction, enhancing regulation for green infrastructure maintenance, regulating GI management, and enhancing awareness, knowledge, and information dissemination about GI. This study provides detailed descriptions of drivers used to overcome identified GI barriers, among which the most significant ones are the drafting of GI legislation; the designation of GI as a common good; the integration of GI principles into all the relevant laws, sublegal acts, and local city decisions; expanding regulatory oversight over private spaces; increasing inspection controls; introducing compensation mechanisms for greenery destruction; mandating greenery cadastres within spatial databases; the prohibition of green space conversions; obliging planners and designers to valorise the existing GI while respecting the interconnectedness and unity of blue–green corridors; offering tax incentives for biodiversity conservation; raising awareness and educating decision-makers, governmental bodies, investors, and the public; supporting projects and non-governmental organisations advocating for GI; implementing "green certification" for facilities incorporating GI features; and introducing ecological index norms in planning in line with contemporary needs for water conservation, soil porosity, connectivity, green roofs, green facades, etc. This study establishes a globally and regionally applicable framework that can be replicated to fulfil broader objectives of sustainable urban revitalisation.

Gaining insight into the limitations and weaknesses of this proposed framework will necessitate evidence gathered through case-study testing. Future research will encompass identifying parameters and subindicators for each indicator, along with the calibration, validation, and assessment of the weaknesses and limitations inherent in the proposed concept. Ultimately, sustainable space is not a local or regional but a global issue that requires diverse transdisciplinary interactions. Our intentions are to persist in research efforts and to establish a composite model based on indicators for assessing RGI performance through conceptualising GI elements as its foundation.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land13050692/s1: Figure S1: Summarised general information about the respondents (2019); Figure S2: Summarised general information about the respondents (2020); Supplementary Material S1: Questionnaire 1 (2018); Supplementary Material S2: Questionnaire 2 (2019); Supplementary Material S3: Questionnaire 3 (2020); Supplementary Material S4: Questionnaire 4 (2023).

Author Contributions: Conceptualisation, D.V., N.V. and B.R.; methodology, D.V., N.V., B.R., N.G. and D.S.; data curation, A.T., N.G. and D.S.; visualisation, D.V., B.R. and M.O.; writing—original draft preparation, D.V., N.V., B.R., N.G., D.S. and M.O.; writing—review and editing, D.V. and B.R.; supervision, M.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The Ministry of Education, Science, and Technological Development, which finances the scientific research of the University of Belgrade, the Faculty of Forestry on the basis of an agreement of the following realisation number: 451-03-65/2024-03/200169.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Dataset available on request from the authors: The raw data supporting the conclusions of this article will be made available by the authors on request.

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

References

1. Jaffe, M.; Zellner, M.; Gonzalez-Meler, M.; Cather, L.; Massey, D.; Ahmed, H.; Elberts, M.; Sprague, H.; Wise, S.; Miller, B. *Using Green Infrastructure to Manage Urban Stormwater Quality: A Review of Selected Practices and State Programs*; Illinois Environmental Protection Agency: Springfield, IL, USA, 2010; p. 143.
2. Kent, J.; Thompson, S.M.; Jalaludin, B. *Healthy Built Environments: A Review of the Literature*; Healthy Built Environments Program, City Futures Research Centre, UNSW: Sydney, Australia, 2011; p. 202.
3. Lafortezza, R.; Davies, C.; Sanesi, G.; Konijnendijk, C.C. Green Infrastructure as a tool to support spatial planning in European urban regions. *iForest* **2013**, *6*, 102–108. [CrossRef]
4. Ely, M.; Pitman, S. *Green Infrastructure; Life Support for Human Habitats*; Botanic Gardens of Adelaide, Department of Environment, Water and Natural Resources: Adelaide, Australia, 2012; p. 380.
5. Dhar, T.K.; Khirfan, L. Climate change adaptation in the urban planning and design research: Missing links and research agenda. *J. Environ. Plan. Manag.* **2017**, *60*, 602–627. [CrossRef]
6. Hurlimann, A.; Moosavi, S.; Browne, G.R. Urban planning policy must do more to integrate climate change adaptation and mitigation actions. *Land Use Policy* **2021**, *101*, 105188. [CrossRef]
7. Naess, P. Urban planning and sustainable development. *Eur. Plan. Stud.* **2001**, *9*, 503–524. [CrossRef]
8. Monteiro, R.; Ferreira, J.C.; Antunes, P. Green infrastructure planning principles: An integrated literature review. *Land* **2020**, *9*, 525. [CrossRef]
9. Mell, I.C. Green infrastructure: Concepts and planning. *FORUM ejournal* **2008**, *8*, 69–80.
10. Cruz-Sandoval, M.; Ortego, M.I.; Roca, E. Tree Ecosystem Services, for Everyone? A Compositional Analysis Approach to Assess the Distribution of Urban Trees as an Indicator of Environmental Justice. *Sustainability* **2020**, *12*, 1215. [CrossRef]
11. Bajić, L.; Vasiljević, N.; Čavlović, D.; Radić, B.; Gavrilović, S. A Green Infrastructure Planning Approach: Improving Territorial Cohesion through Urban-Rural Landscape in Vojvodina, Serbia. *Land* **2022**, *11*, 1550. [CrossRef]
12. Ahern, J. Planning and design for sustainable and resilient cities: Theories, strategies and best practices for green infrastructure. In *Water Centric Sustainable Communities. Planning Retrofitting and Building the Next Urban Environment*; Novotny, V., Ahern, J., Brown, P., Eds.; Willey: Hoboken, NJ, USA, 2010; pp. 135–176.
13. De Sousa, S.; Panagopoulos, T. Environmental Justice in Accessibility to Green. *Land* **2018**, *7*, 134. [CrossRef]
14. Dushkova, D.; Haase, D. Not simply green: Nature-based solutions as a concept and practical approach for sustainability studies and planning agendas in cities. *Land* **2020**, *9*, 19. [CrossRef]
15. Wei, J.; Qian, J.; Tao, Y.; Hu, F.; Ou, W. Evaluating spatial priority of urban green infrastructure for urban sustainability in areas of rapid urbanization: A case study of Pukou in China. *Sustainability* **2018**, *10*, 327. [CrossRef]
16. United Nations Sustainable Development Goals. Available online: https://sustainabledevelopment.un.org/?menu=1300 (accessed on 15 December 2022).
17. Hanna, E.; Comín, F.A. Urban Green Infrastructure and Sustainable Development: A Review. *Sustainability* **2021**, *13*, 11498. [CrossRef]
18. Gould, K.A.; Lewis, T.L. *Green Gentrification. Urban Sustainability and the Struggle for Environmental Justice*, 1st ed.; Agyeman, J., Patel, Z., Eds.; Routledge: London, UK; Taylor & Francis Group: New York, NY, USA, 2017; p. 182.
19. Anguelovski, I.; Irazábal-Zurita, C.; Connolly, J.J.T. Grabbed Urban Landscapes: Socio-spatial Tensions in Green Infrastructure Planning in Medellín. *Int. J. Urban Reg. Res.* **2019**, *43*, 133–156. [CrossRef]

20. Mell, I. Green infrastructure planning: Policy and objectives. In *Handbook on Green Infrastructure*; Sinnett, D., Smith, N., Burgess, S., Eds.; Edward Elgar Publishing: Cheltenham, UK, 2015; pp. 105–123.
21. Benedict, M.A.; McMahon, E.T. *Green Infrastructure: Linking Landscapes and Communities*; Island Press: Washington, DC, USA, 2006; p. 299.
22. Mell, I. *Global Green Infrastructure: Lessons for Successful Policy-Making, Investment and Management*; Routledge: London, UK, 2016; p. 212.
23. Grădinaru, S.R.; Hersperger, A.M. Green infrastructure in strategic spatial plans: Evidence from European urban regions. *Urban For. Urban Green.* **2019**, *40*, 17–28. [CrossRef]
24. Chatzimentor, A.; Apostolopoulou, E.; Mazaris, A.D. A review of green infrastructure research in Europe: Challenges and opportunities. *Landsc. Urban Plan.* **2020**, *198*, 103775. [CrossRef]
25. Kambites, C.; Owen, S. Renewed prospects for green infrastructure planning in the UK. *Plan. Pract. Res.* **2006**, *21*, 483–496. [CrossRef]
26. Koppenjan, J.F. Public–private partnerships for green infrastructures. Tensions and challenges. *Curr. Opin. Environ. Sustain.* **2015**, *12*, 30–34. [CrossRef]
27. Živanović, Z.; Tošić, B.; Nikolić, T.; Gatarić, D. Urban System in Serbia—The Factor in the Planning of Balanced Regional Development. *Sustainability* **2019**, *11*, 4168. [CrossRef]
28. Gajić, A.; Krunić, N.; Protić, B. Classification of Rural Areas in Serbia: Framework and Implications for Spatial Planning. *Sustainability* **2021**, *13*, 1596. [CrossRef]
29. Marković, M.; Cheema, J.; Teofilović, A.; Čepić, S.; Popović, Z.; Tomićević-Dubljević, J.; Pause, M. Monitoring of Spatiotemporal Change of Green Spaces in Relation to the Land Surface Temperature: A Case Study of Belgrade, Serbia. *Remote Sens.* **2021**, *13*, 3846. [CrossRef]
30. Polovina, S.; Radić, B.; Ristić, R.; Kovačević, J.; Milčanović, V.; Živanović, N. Soil erosion assessment and prediction in urban landscapes: A new G2 model approach. *Appl. Sci.* **2021**, *11*, 4154. [CrossRef]
31. Matthews, T.; Lo, A.Y.; Byrne, J.A. Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners. *Landsc. Urban Plan.* **2015**, *138*, 155–163. [CrossRef]
32. Reinwald, F.; Weichselbaumer, R.; Schindelegger, A.; Damyanovic, D. From strategy to implementation: Mainstreaming urban green infrastructure in Austria's spatial planning instruments for climate change adaptation. *Urban For. Urban Green.* **2024**, *94*, 128232. [CrossRef]
33. Lennon, M.; Scott, M.; Collier, M.; Foley, K. Developing green infrastructure 'thinking': Devising and applying an interactive group-based methodology for practitioners. *J. Environ. Plan. Manag.* **2016**, *59*, 843–865. [CrossRef]
34. Hagemann, F.A.; Randrup, T.B.; Sang, Å.O. Challenges to implementing the urban ecosystem service concept in green infrastructure planning: A view from practitioners in Swedish municipalities. *Socio-Ecol. Pract. Res.* **2020**, *2*, 283–296. [CrossRef]
35. Troyer, M.E. A spatial approach for integrating and analysing indicators of ecological and human condition. *Ecol. Indic.* **2002**, *2*, 211–220. [CrossRef]
36. Austin, G. *Green Infrastructure for Landscape Planning: Integrating Human and Natural Systems*, 1st ed.; Routledge: New York, NY, USA, 2014; p. 272.
37. Sproule, W. Content analysis. In *Social Research Methods: An Australian Perspective*; Walter, M., Ed.; Oxford University Press: Melbourne, Australia, 2006; pp. 113–133.
38. Travers, M. Qualitative interviewing methods. In *Social Research Methods: An Australian Perspective*, 2nd ed.; Walter, M., Ed.; Oxford University Press: Melbourne, Australia, 2009; pp. 287–321.
39. Giddens, A. *Sociology*, 5th ed.; Polity Press: Cambridge, UK, 2006; p. 800.
40. Walter, M. *Social Research Methods*, 2nd ed.; Oxford University Press: Melbourne, Australia, 2009; p. 510.
41. Keita, K.; Kourouma, S. Assessment of Policy and Legal Frameworks of Urban Green Infrastructure Development: Republic of Guinea. *Buildings* **2023**, *13*, 1945. [CrossRef]
42. Jayasooriya, V.M.; Ng, A.W.M.; Muthukumaran, S.; Perera, B.J.C. Green infrastructure practices for the improvement of urban airquality. *Urban For. Urban Green.* **2017**, *21*, 34–47. [CrossRef]
43. Xu, F.; Yin, H.W.; Kong, F.H.; Xu, J.G. Developing ecological networks based on MSPA and the least-cost path method: A case study in Bazhong western new district. *Acta Ecol. Sin.* **2015**, *35*, 6425–6434.
44. Shi, X.M.; Qin, M.Z.; Li, B.; Li, C.Y.; Song, L.L. Research on the green infrastructure network in the Zhengzhou-Kaifeng metropolitan area based on MSPA and circuit theory. *J. Henan Univ. Nat. Sci.* **2018**, *48*, 631–638.
45. Antoszewski, P.; Świerk, D.; Krzyżaniak, M.; Choryński, A. Legal Tools for Blue-Green Infrastructure Planning—Based on the Example of Poznań (Poland). *Sustainability* **2024**, *16*, 141. [CrossRef]
46. Bläser, K.; Danielzyk, R.; Fox-Kämper, R.; Funke, L.; Rawak, M.; Sondermann, M. *Urbanes Grün in der integrierten Stadtentwicklung. Strategien, Projekte, Instrumente*; Ministerium für Bauen, Wohnen, Stadtentwicklung und Verkehr des Landes Nordrhein-Westfalen: Düsseldorf, Germany, 2012; p. 184.

47. Castro, P.; Carvalho, R. A Legal Approach to Fostering Green Infrastructure for Improved Water and Energy Efficiency. Part of the book series: Sustainable Development Goals Series (SDGS). In *Blue Planet Law*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 215–226.
48. Wei, J.; Song, Y.; Wang, Y.; Xiang, W. Urban green infrastructure building for sustainability in areas of rapid urbanization based on evaluating spatial priority: A case study of Pukou in China. *Acta Ecol. Sin.* **2019**, *39*, 1178–1188.
49. Gunes, M.; Sahin, S. Model approach for developing urban green network plan focused on historical urban identity: A case study of republican period in Ankara province. *J. Environ. Prot. Ecol.* **2018**, *19*, 1881–1891.
50. Meerow, S.; Newell, J.P. Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. *Landsc. Urban Plan.* **2017**, *159*, 62–75. [CrossRef]
51. Artmann, M.; Kohlera, M.; Meinela, G.; Ganb, J.; Iojac, I.C. How smart growth and green infrastructure can mutually support each other—A conceptual framework for compact and green cities. *Ecol. Indic.* **2019**, *96*, 10–22. [CrossRef]
52. Voghera, A.; Negrini, G.; La Riccia, L.; Guarini, S. Reti ecologiche nella pianificazione locale: Esperienze nella Regione Piemonte. *Reticula* **2017**, *14*, 1–9.
53. Haase, D.; Kabisch, S.; Haase, A.; Andersson, E.; Banzhaf, E.; Baró, F.; Brenck, M.; Fischer, L.K.; Frantzeskaki, N.; Kabisch, N.; et al. Greening cities—To be socially inclusive? About the alleged paradox of society and ecology in cities. *Habitat Int.* **2017**, *64*, 41–48. [CrossRef]
54. Liu, H.-Y.; Jay, M.; Chen, X. The role of nature-based solutions for improving environmental quality, health and well-being. *Sustainability* **2021**, *13*, 10950. [CrossRef]
55. Lai, S.; Zopi, C. Sustainable Spatial Planning Based on Ecosystem Services, Green Infrastructure and Nature-Based Solutions. *Sustainability* **2024**, *16*, 2591. [CrossRef]
56. European Commission. EU Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives. Document No. 52020DC0380. COM/2020/380 Final. 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0380&from=EN (accessed on 4 April 2024).
57. European Commission. Forging a Climate-Resilient Europe—The New EU Strategy on Adaptation to Climate Change. Document No. 52021DC0082. COM/2021/82 Final. 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN (accessed on 4 April 2024).
58. European Commission. The European Green Deal. Document No. 52019DC0640. COM/2019/640final. 2019. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM:2019:640:FIN (accessed on 4 April 2024).
59. Tzoulas, K.; Korpela, K.; Venn, S.; Yli-Pelkonen, V.; Kaźmierczak, A.; Niemela, J.; James, P. Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landsc. Urban Plan.* **2007**, *81*, 167–178. [CrossRef]
60. Forest Research. *Benefits of Green Infrastructure*; Report to Defra and CLG; Forest Research, Farnham: Surrey, UK, 2010; p. 196.
61. Toth, A.; Timpe, A. Exploring urban agriculture as a component of multifunctional green infrastructure: Application of figure-ground plans as a spatial analysis tool. *Morav. Geogr. Rep.* **2017**, *25*, 208–218. [CrossRef]
62. Williams, F. Evidence of paucity of residential green spaces from the normalized difference vegetation index (NDVI) in Metropolitan Lagos, Nigeria. *Acta Hortic. Regiotect.* **2022**, *25*, 51–59.
63. Pochodyła, E.; Jaszczak, A.; Illes, J.; Kristianova, K.; Joklova, V. Analysis of green infrastructure and nature-based solutions in Warsaw—Selected aspects for planning urban space. *Acta Hortic. Regiotect.* **2022**, *25*, 44–50. [CrossRef]
64. Drake, J.; Guo, Y. Maintenance of wet stormwater ponds in Ontario. *Can. Water Resour. J.* **2008**, *33*, 351–368. [CrossRef]
65. Davies, C.; Hansen, R.; Rall, E.; Pauleit, S.; Lafortezza, R.; de Bellis, Y.; Santos, A.; Tosics, I. *Green Infrastructure Planning and Implementation: Report 5.1: The Status of European Green Space Planning and Implementation Based on an Analysis of Selected European City-Regions, Work Packege 5: Green Infrastructure Planning and Implementation. Green Surge Project*; University of Copenhagen: Copenhagen, Denmark, 2015. Available online: https://greensurge.eu/working-packages/wp5/files/D_5.1_Davies_et_al_2015_Green_Infrastructure_Planning_and_Implementation_v2.pdf (accessed on 25 December 2023).
66. O'donnell, E.C.; Lamond, J.E.; Thorne, C.R. Recognising barriers to implementation of Blue-Green Infrastructure: A Newcastle case study. *Urban Water J.* **2017**, *14*, 964–971. [CrossRef]
67. Pauleit, S.; Zölch, T.; Hansen, R.; Randrup, T.B.; van den Bosch, C.K. Nature-Based Solutions and Climate Change—Four Shades of Green. In *Nature-Based Solutions to Climate Change Adaptation in Urban Areas*; Springer: Cham, Switzerland, 2017; pp. 29–49.
68. Hansen, R.; Pauleit, S. From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. *Ambio* **2014**, *43*, 516–529. [CrossRef] [PubMed]
69. Pantaloni, M.; Marinelli, G.; Santilocchi, R.; Neri, D. Sustainable Management Practices for Urban Green Spaces to Support Green Infrastructure: An Italian Case Study. *Sustainability* **2022**, *14*, 4243. [CrossRef]
70. Langemeyer, J.; Gómez-Baggethun, E.; Haase, D.; Scheuer, S.; Elmqvist, T. Bridging the gap between ecosystem service assessmentsand land-use planning through Multi-Criteria Decision Analysis (MCDA). *Environ. Sci. Policy* **2016**, *62*, 45–56. [CrossRef]
71. Klimanova, O.A.; Illarionova, O.I. Green infrastructure indicators for urban planning: Applying the integrated approach forrussian largest cities. *Geogr. Environ. Sustain.* **2020**, *13*, 251–259. [CrossRef]
72. Inzunza-Acedo, B.E. Media as source of information in the construction of social representations. *Comun. Soc.* **2017**, *29*, 167–182.

73. Metastasio, R.; Bocci, E.; Passafaro, P.; Carnovale, F.; Zenone, V. The Social Representation of Sustainable Mobility: An Exploratory Investigation on Social Media Networks. *Sustainability* **2024**, *16*, 2833. [CrossRef]
74. Pakzad, P.; Osmond, P. Developing a sustainability indicator set for measuring green infrastructure performance. *Procedia Soc. Behav. Sci.* **2016**, *216*, 68–79. [CrossRef]

land

MDPI

Article

Spatio-Temporal Assessment of Urban Carbon Storage and Its Dynamics Using InVEST Model

Richa Sharma [1], Lolita Pradhan [1], Maya Kumari [1,*], Prodyut Bhattacharya [2], Varun Narayan Mishra [3] and Deepak Kumar [4,*]

[1] Amity School of Natural Resources & Sustainable Development, Amity University, Sector—125, Noida 201313, India; richasharma1987@gmail.com (R.S.); lpradhan@amity.edu (L.P.)
[2] School of Environmental Management, Block 'A', Guru Gobind Singh Indraprastha University, New Delhi 110078, India; prodyutbhattacharya@yahoo.com
[3] Amity Institute of Geoinformatics and Remote Sensing, Amity University, Sector—125, Noida 201313, India; vnmishra@amity.edu
[4] Atmospheric Science Research Center (ASRC), State University of New York (SUNY), Albany, NY 12226, USA
* Correspondence: mkumar10@amity.edu (M.K.); dkumar3@albany.edu or deepakdeo2003@gmail.com (D.K.)

Abstract: Carbon storage estimates are essential for sustainable urban planning and development. This study examines the spatio-temporal effects of land use and land cover changes on the provision and monetary value of above- and below-ground carbon sequestration and storage during 2011, 2019, and the simulated year 2027 in Noida. The Google Earth Engine-Random Forests (GEE-RF) classifier, the Cellular Automata Artificial Neural Network (CA-ANN) model, and the InVEST-CCS model are some of the software tools applied for the analysis. The findings demonstrate that the above- and below-ground carbon storage for Noida is 23.95 t/ha. Carbon storage in the city increased between 2011 and 2019 by approximately 67%. For the predicted year 2027, a loss in carbon storage is recorded. The simulated land cover for the year 2027 indicates that if the current pattern continues for the next decade, the majority of the land will be transformed into either built-up or barren land. This predicted decline in agriculture and vegetation would further lead to a slump in the potential for terrestrial carbon sequestration. Urban carbon storage estimates provide past records to serve as a baseline and a precursor to study future changes, and therefore more such city-scale analyses are required for overall urban sustainability.

Keywords: Carbon Storage And Sequestration (CSS); Cellular Automata-Artificial Neural Network (CA-ANN) model; Google Earth Engine (GEE); Noida

Citation: Sharma, R.; Pradhan, L.; Kumari, M.; Bhattacharya, P.; Mishra, V.N.; Kumar, D. Spatio-Temporal Assessment of Urban Carbon Storage and Its Dynamics Using InVEST Model. *Land* **2024**, *13*, 1387. https://doi.org/10.3390/land13091387

Academic Editor: Thomas Panagopoulos

Received: 15 July 2024
Revised: 13 August 2024
Accepted: 25 August 2024
Published: 29 August 2024

1. Introduction

Urban sustainability is directly connected to the Sustainable Development Goals (SDGs), such as the goals concerning Sustainable Cities and Communities (Goal 11), Responsible Consumption and Production (Goal 12), and Climate Action (Goal 14) [1]. The SDGs call for nationally owned and region-specific development plans or strategies [2]. Urban centres emanate three-fourths of the world's total carbon dioxide (CO_2) emissions resulting from several anthropogenic activities [3]; therefore, it is imperative that cities take the lead rather than just depending on national plans and strategies [4]. They can achieve sustainability by reducing their CO_2 emissions and aiming for carbon (C) neutrality through carbon storage and sequestration (CSS) [5].

According to the IPCC [6], the major five carbon pools of a terrestrial ecosystem involving biomass are above-ground biomass (AGB), below-ground biomass (BGB), dead wood, litter, and soil organic matter (SOC). AGB includes all the visible and living biomass above the soil-stem, branches, bark, seeds, and foliage and constitutes the major portion of the terrestrial carbon pool. Changes in the land use system have a direct impact on above-ground biomass. BGB includes all living roots excluding fine roots and plays a pivotal role by transferring and storing carbon in the soil. SOC is the carbon produced from decomposing plants, bacterial and fungal growth, and metabolic activities of living organisms, and is one of the major contributors to carbon stocks [7]. Given that they only make up a small portion of the carbon stocks in forests, the dead mass of litter and woody debris is not a significant carbon sink [8]. The aggregate amount of C stored in the terrestrial C pools at any specified time is the carbon stock or store. The change in carbon stocks over time due to natural or anthropogenic activities gives the amount of C sequestered in the C pools. One of the essential prerequisites for cities to achieve C neutrality and sustainability is to have an accurate evaluation of the C sequestration potential of the urban greens [9]. The ability of urban greens to lock in C and mitigate elevated CO_2 levels has caught the attention of the research community all over the world [10–13].

Understanding land use dynamics and their effect on C sequestration capacity is vital for sustainable urban development. Land processes have a pivotal role in the global and regional C cycle through photosynthesis, respiration, volcanoes, and anthropogenic activities like afforestation and deforestation [14], altering both sources and sinks of carbon. Fast-paced development across the world, especially in urban centres, is leading to rapid transformation of the land cover and its use. Land cover and land use (LULC) changes caused by both natural and anthropogenic activities lead to changes in the carbon stock of urban centres, which further degrades ecosystem service functions [15]. Therefore, understanding land use dynamics and their effect on carbon sequestration capacity is vital for sustainable urban development [16].

Several methodologies have been employed to explore the relationship between land use dynamics and their effect on carbon storage capacity, such as field investigations [13,17] and remote sensing tools [18,19]. One of the earliest studies using a simulation model to understand the interaction between the C pools in the biosphere, atmosphere, and the ocean was done by Goudriaan J. [20]. Subsequently, various models have increasingly been used to simulate, project, and evaluate the consequences of urban sprawl on local C sequestration capacity at various spatial and temporal scales, such as DLEM (the Dynamic Land Ecosystem Model) [21], the CESVA model (Carbon Exchange in the Vegetation-Soil-Atmosphere System) [22], and the CASA (Carnegie Ames Stanford Application) productivity model [23], etc. In developed nations such as in Europe and North America, there are several works wherein records of urban vegetation and C stock have been estimated using other models like i-Tree Eco [24,25], CITYgreen [23,26], and the UFORE (Urban Forest Effects) model [27,28]. These freely available tools aid in the inventorisation of local flora and provide species-specific data. Such models make the estimation of the C storage of urban greens simpler and efficient, and are therefore widely used in urban areas. However, the applicability of these tools is limited for other geographical locations because of the considerable variation in the geography, climate, and vegetation types [29]. For developing countries like India, such modelling and assessment tools are unavailable and national forest inventories most often do not include urban trees [30]. Because of the lack of such city-scale inventories, most of the vegetation studies and C stock estimations are still dependent on field measurements and limited area inventory data [31–40].

Recently, the Integrated Valuation of Ecosystem Services and Tradeoffs-Carbon Storage and Sequestration (InVEST-CSS) model, started under the Natural Capital Project [41], has been used in several studies to ascertain the C storage capacity of urban areas based on land use/cover changes [42–47]. This CSS module of the model calculates the present amount of C stored and assesses the quantity of sequestered cover time for an area. This model offers a simple and authentic method of estimating C storage with minimum input parameters [48]. Polasky et al. (2011) [49] examined the effects of real and different scenarios of LULC on C-holding capacity in Minnesota, USA, from 1992 to 2001 using the InVEST model. They also suggested different strategies to manage land to enhance C-storage capacity. Leh et al. (2013) [50] also examined the effects of LULC on Ghana's C stock from 2000 to 2009 at the national level using the same tool. Delphin et al. (2013) [51] assessed the effects of hurricanes on the watersheds and forests of Florida and subsequent C loss. Liu et al.

(2018) [52] employed InVEST to study the fluctuation in C stock in northern Shaanxi at different scales. Abdo and Satyaprakash (2021) [53] analysed the consequences of LULC on C storage in Addis Ababa city, Ethiopia, from 1988 to 2018 and simulated it for 2028–2038 using InVEST. InVEST was also used to evaluate the C stored in the Jiroft plain, Iran, by Adelisardou et al. (2022) [54] and in Uva province in Sri Lanka by Piyathilake et al. (2022) [55]. The model has also been applied in other areas like Guilin, China, by He et al. (2023) [56], Nador, Morocco, by Rachid et al. (2024) [57] and Pakistan by Zafar et al. (2024) [58].

In India, there has been limited applicability and use of InVEST for the analysis of C storage capacity in natural landscapes and it has not been extended to urban areas. For example, Gupta et al. (2017) [59] studied the C storage in the Bhidalna microwatershed, Dehradun District of Uttarakhand state in India. The tool has also been used to analyse the dynamic pattern of C sequestration in the Periyar Tiger Reserve [60], Sariska Tiger Reserve [61], Sundarban Biosphere Reserve [62], and Askot Wildlife Sanctuary [63].

Therefore, the primary objectives of this study are to: (i) explore the spatio-temporal dynamics of the above- and below-ground C storage of an incessantly expanding urban centre in India-Noida from 2011 to 2019 using the InVEST-CSS model; (ii) forecast the amount that will be stored in the future year 2027, through the analysis of alterations in the land use over these years; and (iii) estimate the monetary cost of the observed variation in the C stock over the years. Urban soils are highly heterogeneous because of the presence of concrete, asphalt, metals, plastics, and many contaminants. Soil sealing with impermeable surfaces, such as roads and pavements, leads to a reduction in SOC content in urban areas [64–66]. Chien & Krumins (2022) [67] also reports that SOC in natural habitats is significantly higher than that of urban green spaces and urban intensive habitats. Therefore, this study is limited to the evaluation of above- and below-ground C only, despite SOC being an important contributor to the terrestrial carbon pool.

Correct estimates of the C stored in cities are very important to highlight and understand the function of UGS in the atmospheric C balance. To understand and better manage the mitigation potential of green spaces, verifiable and reasonable estimates of the C sequestered from cities are needed. The findings of this study will help urban planners and managers to better comprehend the land use dynamics, their drivers, and the subsequent effect on the C stocks of the city.

2. Study Location

This study is carried out in relation to Noida city, an abbreviation for the New Okhla Industrial Development Authority. It is situated in the district of Gautam Buddha Nagar in the state of Uttar Pradesh, in northern India (Figure 1).

Climate—Noida has a blisteringly hot and humid environment for a large portion of the year. The climate stays hot during the summer, i.e., from March to June, and the temperature ranges between 48 and 28 °C. Monsoon prevails from mid-June to mid-September with normal precipitation of 93.2 cm. Temperatures tumble down to as low as 3–4 °C at the peak of the winter due to the cold waves from the Himalayan region, which make the winters in Noida chilly and harsh. Noida additionally has haze and smog in winter, decreasing the overall visibility in the city.

Soil—Much of the land in Noida is not fertile and the agricultural yield is low. It is in the flood fields of the Yamuna River on one side and the Hindon River on the other and is situated on the old stream bed. Pedogenic material is mostly formed by sandy and loamy fluvisols [68] or fluverine alluvial soils [69] Wheat, rice, sugar cane, and millets are the primary crops planted in the area.

Vegetation—The vegetation in the space falls under the classification of the subtropical deciduous sort, although at present it does not have any extent of forest. Noida Authority has built up various forms of green spaces within the city like green belts, gardens, parks, avenue plantations, and vertical gardens. Every residential sector in the city has a park/playground, adding to the overall verdancy of Noida and providing respite to the Noida citizens. Approximately 10–12% of the land is allocated to parks, playgrounds, and other open spaces in each of the sector. The city authorities have also designed and developed several big green spaces for the benefit of the residents.

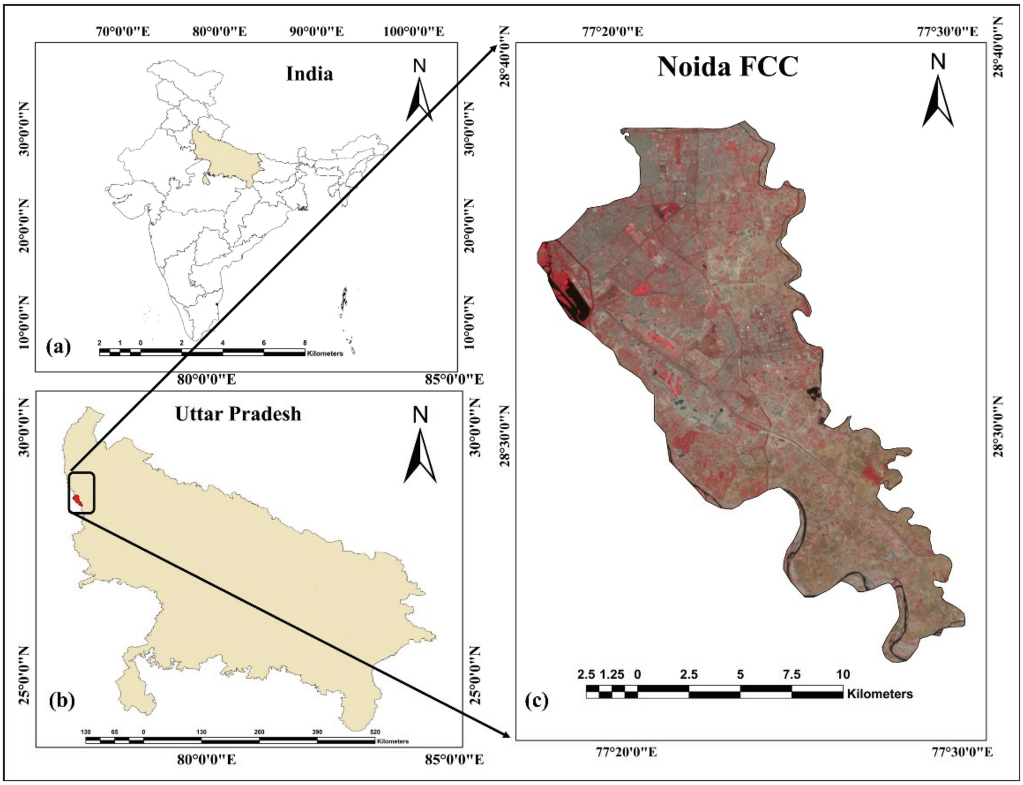

Figure 1. Study Location (**a**) Map of India; (**b**) Map of Uttar Pradesh; (**c**) Satellite Landsat 8 Image of Noida City.

Geomorphology—The landscape of this region is for the most part plain with a gentle incline fluctuating between 0.2 and 0.1 percent from north-east to south-west. The highest and lowest height ranges between 204 m and 195 m above the mean sea level (MSL) close to the villages Parthala Khanjarpur in the northeast and Garhi in the southwest, respectively. Most of Noida territory is under 200 m mean ocean level.

As a satellite city around the national capital, New Delhi, it harbours several multinational companies (MNCs) and industries. The city is burgeoning rapidly with rampant urbanisation and industrialisation. The presence of good infrastructure, educational facilities, employment opportunities, and modern residential spaces surrounded with greenery has attracted mass migration and unplanned growth in the city over the years. Extensive urbanisation started around 2010-11 in Noida, such as the construction of the Yamuna Expressway, the Indian motor racing circuit, the Rashtriya Dalit Prerna Sthal, the Green Garden, and several residential spaces. The Noida Master Plan 2011 which was revised in 2006 for the perspective year of 2021, also proposed a total of 14964 hectares of land for the development of urban activities.

An estimation of CSS at the local, regional, and landscape levels is crucial to assist India's nationally determined contributions (NDCs) to the United Nations Framework Convention on Climate Change (UNFCCC) [70]. The 'National Mission for a Green India', one of the sub-missions under the National Action Plan on Climate Change (NAPCC), has also identified priority research areas such as to study vegetation response to climate change and benchmarking the C-capture potential of ecosystems, etc. Noida is one of the largest planned cities in India; still, there are no accurate estimates of the C storage of the city. There is a paucity of work highlighting the contribution of spatio-temporal dynamics of land use and its carbon storage to mitigate urban CO_2 emissions in such Indian metropolitan cities. Therefore, Noida was taken as the study area for this study so that the analysis could be replicated to other urban agglomerations within and outside India.

3. Materials and Methods

The overall methodology of this study is illustrated in Figure 2 and detailed further below.

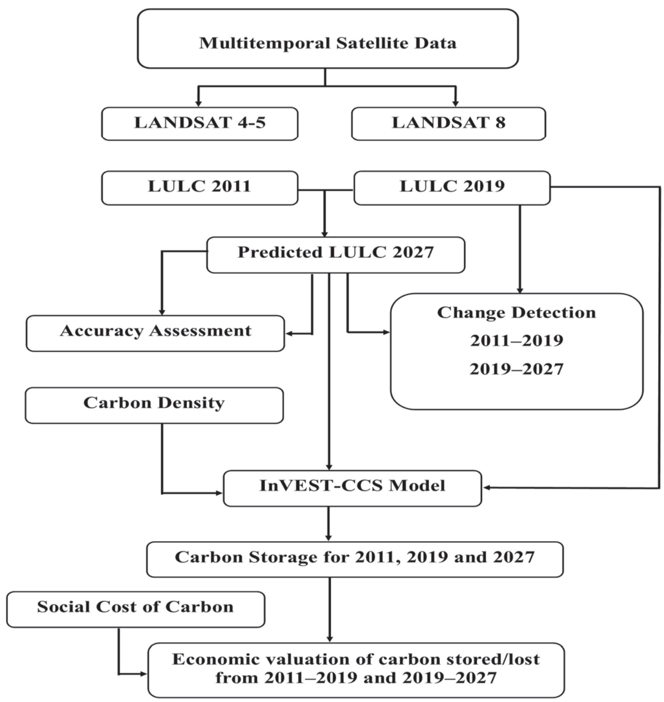

Figure 2. Overall Methodology.

3.1. Satellite Dataset and Software Used

Multi-temporal satellite imagery was retrieved from USGS (the United States Geological Survey) for two time periods—2011 and 2019. The details of the imagery employed for this study are as follows (Table 1). The following software were used for analysing satellite data—ERDAS Imagine 14, ArcGIS10.2, and Quantum GIS 2.18.

Table 1. Details of Satellite Imageries.

S. No.	Dataset	Retrieved on	Spatial Resolution	Retrieved from
1.	LANDSAT 5	22 April 2011	30 m	United States Geological Survey (USGS)
2.	LANDSAT 8	28 April 2019	30 m	

3.2. Derivation of Landuse and Landcover and Accuracy Assessment

LULC maps were prepared using Landsat Satellite data for the years 2011 and 2019, respectively. Google Earth Engine's Random Forest classification method was applied to delineate five LULC categories, viz., Built-up land, Vegetation, Agricultural/fallow land, Barren land, and Water bodies. Owing to its high accuracy and easy computation, RF has proven to be the first choice for the classification of urban landscapes [71] and was therefore used in preparing LULC in this study. The final step after the LULC classification is to conduct an accuracy evaluation to quantify the success of the method in correctly allocating pixels to the appropriate land cover classes.

The Google Earth Engine (GEE) is a cloud-based interface for the analysis of geospatial data, addressing the major issues related to the storage, processing, and analysis of immensely large datasets. The GEE library provides access to both types of classification techniques. A few of the supervised classification techniques are the support vector machine (SVM), random forest (RF), and the classifiers classification and regression tree (CART) [72]. Random Forest is a popular supervised classification method featured in GEE [73]. An RF model combines field measurements and remotely sensed data using multiple decision trees or 'the forest'. Also called the ensemble classifier, RF is a non-parametric classification algorithm. The most popular class is voted after each decision tree classifies the data independently.

3.3. Prediction of LULC of Future Years

LULC for the future year 2027 was simulated using MOLUSCE plugin in the QGIS software, which offers a user-friendly and intuitive plugin for users to perform modelling and simulation. In ArcMap, a set of spatial variables with the same picture element size, location, and fixed scale was created, including slope, aspect, and road. The whole set of data was then imported into the MOLUSCE Plugin, to generate an LULC map and determine the trend of change for the study. Annual percentage change in area was computed by the plugin and a transition grid illustrating the number of picture elements transforming to another LULC was displayed. It also created an area change map that illustrates the changes in the land from 2011 to 2019 and from 2019 to 2027. The LULC transition potential was modelled by MOLUSCE using Artificial Neural Network (ANN), Multi-Criteria Evaluation (MCE), Weights of Evidence (WOE), and Logistic Regression (LR) techniques. The ANN model was used in this study to simulate spatial LULC change because it is very good at capturing the complicated non-linear behaviour of ecosystems [74]. The plugin utilised a Cellular-Automata Simulation to predict the change in LULC. The input data used to model potential land use in 2027 was defined as the LULC maps from 2011 and 2019. This model was not based on any anthropogenic or natural processes, but rather on the past change.

3.4. Estimation of Carbon Storage

In this analysis, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)—Carbon Storage and Sequestration (CSS) model developed by the Natural Capital Project [75] was employed to determine the carbon sequestration potential of Noida. Though SOC is a significant contributor to terrestrial C, this study only used AGB and BGB for the computation of C stored. Using the LULC maps generated in the previous steps and C density as the input, the CCS module of the model can calculate the total amount of C stored in the landscape. The carbon density of any vegetation is usually calculated by using the biomass and total C content coefficient, while the carbon density of the soil is obtained by considering the bulk density, organic matter content, and thickness of the soil [76]. Parameters like biomass, bulk density, organic matter content, and thickness of the soil are determined through field surveys and chemical analysis. The C densities of various LULC types in this study were determined using secondary data from FSI and IPCC [6,61,77,78]. The output consists of storage, sequestration, and aggregate totals, represented as Mg/pixel, and maps C storage densities to LULC maps. The total C sequestered or lost over time was also computed using the current and prospective LULC maps. The final step involved assessing the monetary value of C sequestration/loss over time, rather than storage, for each scenario. Three pieces of information were needed for this calculation: the annual discount rate, the monetary worth of each unit of C, and the evolution of the cost of C sequestration. The monetary value of a metric tonne of C sequestered was taken to be $86 with a 3% of market rate of discount, and zero change in the cost of C in a year [79].

4. Results and Discussion

4.1. Spatio-Temporal Analysis of Land Use and Land Cover

Understanding the dynamics of the altering landscape and making future predictions are made easier by the spatial and temporal analysis of the change in urban land cover. Both the satellite datasets from 2011 and 2019 underwent supervised classification using the appropriate training signatures for the major LU/LC classes, including built-up land, barren land, vegetation, waterbodies, and agriculture/fallow land. The results of the land use/land cover are given in Table 2 and the classified outputs are given in Figure 3.

Table 2. LULC Statistic—2011, 2019, and 2027.

LULC Classes	Year 2011		Year 2019		Year 2027		Change (2011–2019)		Change (2019–2027)	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Agricultural/ Fallow land	86.74	41.00	27.68	13.09	24.10	11.39	−59.06	−27.91	−3.58	−1.70
Barren land	13.84	6.55	12.84	6.07	14.30	6.76	−1.00	−0.48	1.46	0.69
Waterbodies	8.34	3.93	4.64	2.18	4.30	2.03	−3.70	−1.75	−0.34	−0.15
Built-up land	74.70	35.30	106.77	50.46	120.32	56.88	32.07	15.16	13.55	6.42
Vegetation	27.92	13.22	59.61	28.20	48.52	22.94	31.69	14.98	−11.09	−5.26
Total	211.54	100	211.54	100	211.54	100				

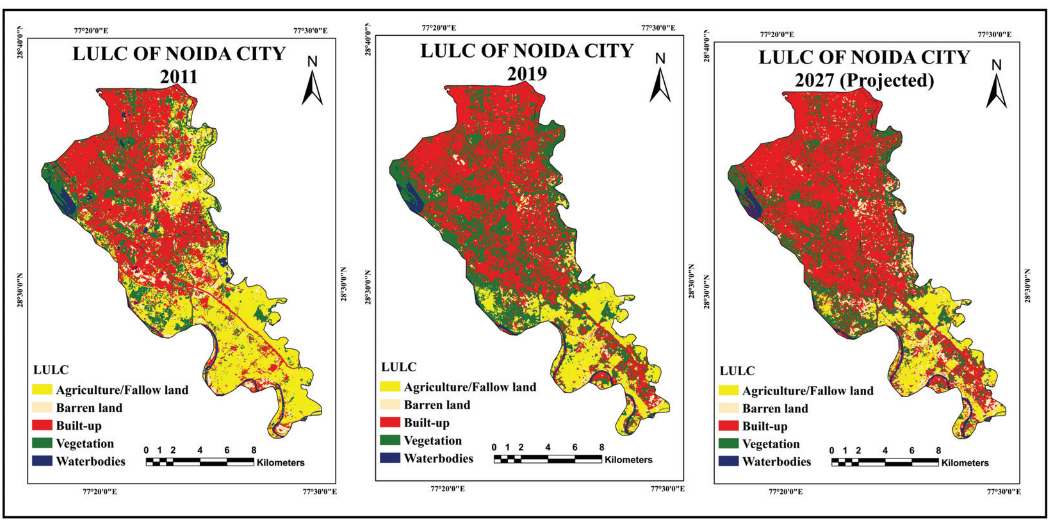

Figure 3. LULC of Noida City 2011, 2019 and 2027.

The classified map of 2011 shows a high concentration of built-up land in the northwestern part and moderate density in the central part of Noida City. It is evident from the LULC of 2019 that the direction of the urban sprawl is extending further into the northeast and south of the city. It is to be noted that the area under vegetation and the built-up categories were 27.92 km^2 and 74.7 km^2, respectively, in 2011, which further increased to 59.61 km^2 and 106.77 km^2, respectively, in 2019. On the other hand, the agricultural/fallow land area, which was 86.74 km^2 in 2011, shrunk to 27.68 km^2 in 2019. The area under barren land and water body showed a marginal decrease in 2019. Thus, most of the increment in the built-up land came about because of the transformation of agricultural land into other land use classes, in which cultivated lands and other barren terrains were replaced by building, roads, pavements, and different infrastructures which likewise brought about the increment in urban vegetation as well.

For the simulated LULC of the year 2027, it can be observed that there will be a large increment in built-up land (6.42%) and a slight increase in barren land (0.69%). Such increment in the barren and built-up area can be attributed to future construction activities and the transformation of agricultural land, respectively. The prediction indicated that an additional area of 32.07 km^2 will be transformed into fallow land, whereas not much change is expected in waterbodies. However, agricultural/fallow land and vegetation will both decrease year after year, resulting in a potential loss by 2027. This method is based on past changes in pixels according to the LULC of 2011 and 2019. If the present trend persists, the majority of the other land cover classes will be replaced by built-up or barren land, as indicated by the projected land cover for 2027. The capacity for terrestrial C sequestration will further decrease because of the anticipated reduction in the area used for agriculture and urban vegetation.

4.2. Accuracy Assessment

An accuracy assessment verifies the accuracy of the pixel distribution and the viability of maximum likelihood in urban mapping. The final image had 92% overall accuracy in 2011 and 93% in 2019. The κ coefficient was 0.93 in 2011, followed by 0.89 in 2019 (Tables 3 and 4).

Table 3. Accuracy Assessment Error Matrix (2011).

Reference	Classes	Agricultural/ Fallow Land	Barren Land	Built-Up Land	Vegetation	Water Bodies	Row Total	Producer Accuracy (%)	User Accuracy (%)	Overall Accuracy (%)	κ Coefficient
Classified	Agricultural/ Fallow land	**20**	1	2	1	0	24	100.00	83.33	91.6667	0.93
	Barren land	0	**5**	0	0	0	5	83.33	100.00		
	Built-up land	0	0	**20**	0	0	20	90.91	100.00		
	Vegetation	0	0	0	**8**	0	8	88.89	100.00		
	Water bodies	0	0	0	0	**3**	3	100.00	100.00		
	Column Total	20	6	22	9	3	**60**				

Table 4. Accuracy Assessment Error Matrix (2019).

Reference	Classes	Agricultural/Fallow Land	Barren Land	Built-Up Land	Vegetation	Water Bodies	Row Total	Producer Accuracy (%)	User Accuracy (%)	Overall Accuracy (%)	κ Coefficient
Classified	Agriculture/Fallow land	**7**	0	0	1	0	8	87.50	87.50	93.33	0.89
	Barren land	0	**8**	1	0	0	9	88.89	88.89		
	Built-up land	0	1	**24**	0	0	25	96.00	96.00		
	Vegetation	1	0	0	**15**	0	16	93.75	93.75		
	Water bodies	0	0	0	0	**2**	2	100.00	100.00		
	Column total	8	9	25	16	2	**60**				

The κ statistic was used to determine the validation of the simulated LULC. The predicted LULC map's accuracy rate was 94.88 percent, with an overall κ of 0.92 and a κ histogram of 0.93 (Table 5).

Table 5. Validation of simulated LULC—2027.

Method	Correctness %	Overall κ	κ (Histogram)
Artificial Neural Network (ANN)	94.88	0.92	0.93

4.3. Impact of Land Use Change on C Storage

The C storage of the city was estimated using the InVEST (v. 3.11.0) software. The amount of C stored in every grid is calculated using LULC maps and the C density of every category of land use. As per Table 6, the C stored in vegetation is the maximum for all the years, followed by agricultural land in 2011 and built-up land in 2019 and 2027, respectively. For the year 2011, the C stored in vegetation is 234,499.39 metric tonnes (77.27%) followed by agricultural land with 43,176.27 metric tonnes (14.23%) and built-up land as 22,943.98 metric tonnes (7.56%), respectively. Subsequently in 2019, the overall C storage of the city increased by approximately 67% to 506,558.32 metric tonnes, distributed across built-up land, agricultural/fallow land, barren land, and vegetation. Though it is seen that a higher quantity of C is stored in the vegetation and built-up class, a drastic decrease in the C storage in agricultural classes is observed. A slight drop in C storage is observed in barren land in 2019. For the predicted year 2027, an overall C storage of 454,591.85 metric tonnes is recorded, highlighting a loss in C storage in the future. It is noteworthy that though the vegetation increased between 2011 and 2019, an increase in built-up and barren land, attributed to urbanisation, will potentially cause C loss in the city in the coming years. Li et al. (2002) [44] also reported a similar trend wherein the conversion of cultivated land to construction land was the main reason for the C storage loss in Changchun city in China.

Table 6. Carbon storage in each LULC year wise.

LULC	Carbon Density (t/ha)	Total Carbon (t)			C in Each LULC (%)			Change in Carbon (t)	
		2011	2019	2027	2011	2019	2027	2011–2019	2019–2027
Agricultural/fallow land	5	43,176.27	13,446.41	12,989.88	14.23	2.65	2.86	−29,729.87	−456.53
Barren land	2	2850.75	2269.44	3460.00	0.94	0.45	0.76	−581.32	1190.56
Waterbodies	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Built-up land	3	22,943.98	30,696.46	35,984.99	7.56	6.06	7.92	7752.48	5288.53
Vegetation	82.17	234,499.39	460,146.03	402,156.99	77.27	90.84	88.47	225,646.64	−57,989.04
Total		303,470.40	506,558.34	454,591.85				203,087.93	−51,966.48

4.4. Carbon Sequestration Map

The CCS module of the software condensed the findings into an output image that represented the dispensation of C storage in Noida. In addition, the findings demonstrated that the city of Noida, which encompasses an area of land measuring 21,154 hectares, is currently storing 506,558.34 metric tonnes of C, distributed across all land classes. Therefore, the C storage for Noida city is 23.95 t/ha. The results are compared with other cities all over the world (Table 7). The C stored is less for Noida city in comparison to several other cities across the world.

Table 7. Carbon storage in urban vegetation in various cities/countries.

S. No.	City/Country	Carbon Storage (t/ha)	References
1.	Bolzano, Italy	0.75	[27]
2.	Jersey City, US	5.02 ± 0.68	[28]
3.	New Delhi, India	4.65	[80]
4.	Cities in Middle Korea	4.70–7.20	[81]
5.	Barcelona, Spain	11.20	[82]
6.	Leipzig, Germany	11.81 ± 3.25	[83]
7.	West Africa	14.00	[84]
8.	Canada	20.83	[85]
9.	**Noida, India**	**3.95**	**Present work**
10.	Baltimore, US	25.28 ± 3.16	[28]
11.	Hangzhou, China	30.25	[86]
12.	Leicester, UK	31.60	[29]
13.	Karlsruhe, Germany	32.30	[87]
14.	Shenyang, China	33.22 ± 4.32	[88]
15.	Atlanta, US	35.74 ± 2.69	[28]
16.	Beijing, China	43.70 ± 6.65	[89]
17.	Tripura, India	45.41	[90]
18.	Sacramento, US	46.91 ± 22.64	[91]
19.	Kumasi, Ghana	111.00	[92]

For both the years 2011 and 2019, the above-ground C stored ranged from 0 to 5.30 metric tonnes per pixel while the below-ground C ranged from 0 to 2.08 metric tonnes per pixel (Figures 4 and 5). The total C stored per pixel ranged from 0 to 7.39 metric tonnes for 2011, 2019 and the future year 2027 (Figure 6).

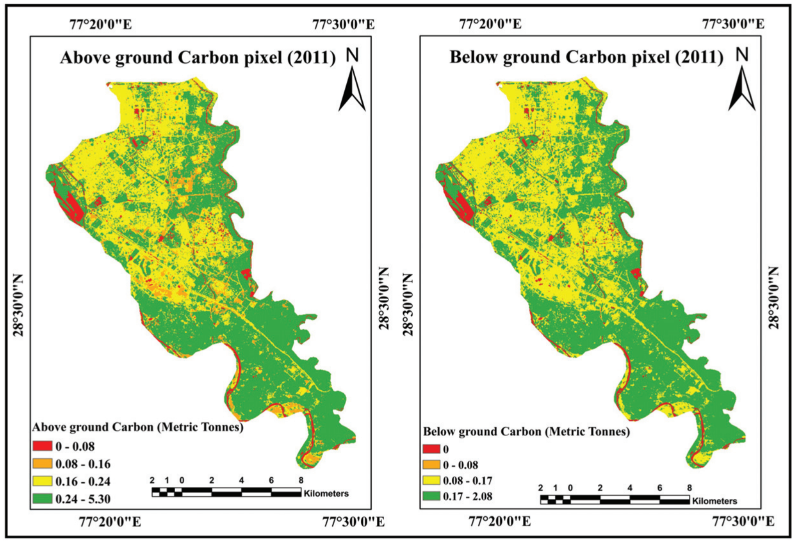

Figure 4. Above- and below-ground carbon per pixel (2011).

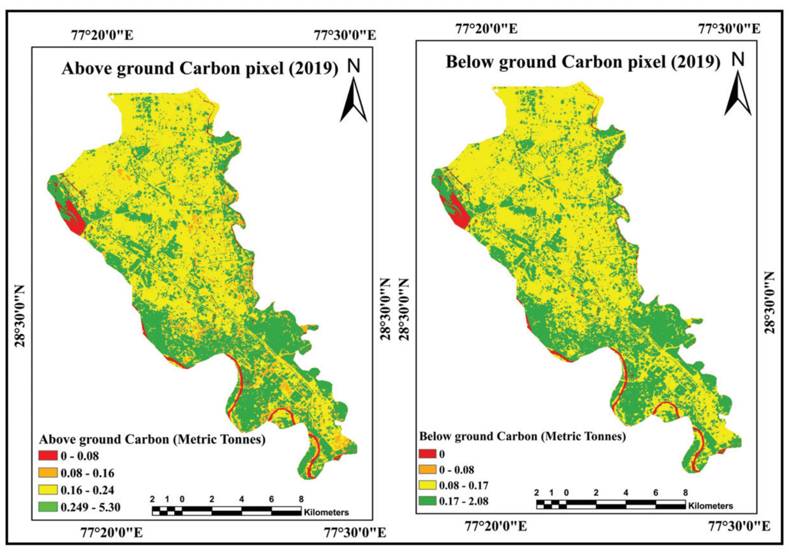

Figure 5. Above- and below-ground carbon per pixel (2019).

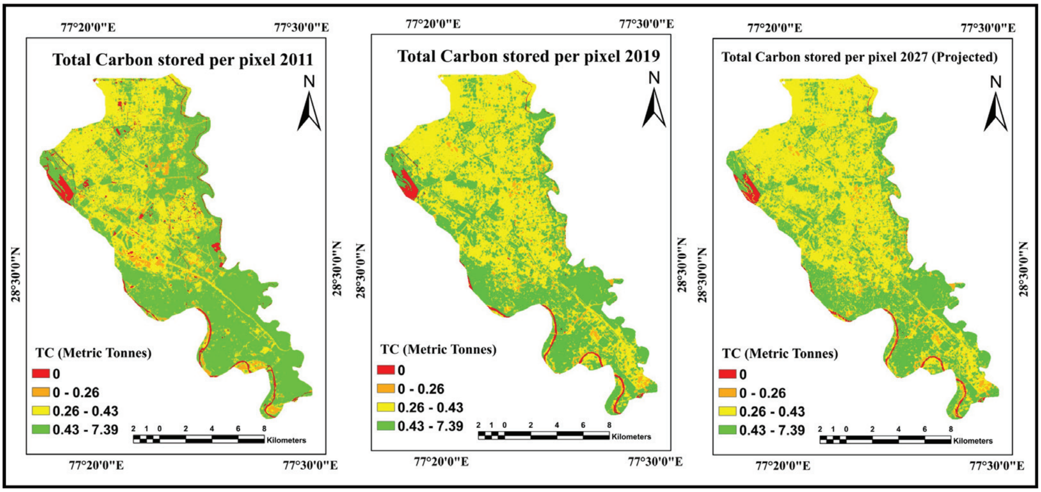

Figure 6. Total carbon stored per pixel (2011, 2019 and 2027).

The C stock per pixel is the same for all the three years and ranged from 0 to 7.39 metric tonnes. However, due to the transition in the LULC from one class to another class, the total C in each class changed for each year. The total C sequestered per pixel between 2011 to 2019 ranged from −7.39 to 7.39 and between 2019 and 2027, it ranged from −7.21 to 7.39 (Figure 7). Positive values indicate that C is being sequestered, while negative values indicate that C is being lost to the atmosphere. C sequestration is designated by positive values, whereas C loss to the atmosphere is implied by negative values.

If proper future urban planning and a substantial increment in green spaces are achieved, a higher C-storing capacity amidst built-up land, with a slightly lower percentage of C stored in vegetation and agriculture, can be achieved by the year 2027. The results obtained are corroborated by Jiang [93], who validated that reckless urbanisation in the Changsha-Zhuzhou-Xiangtan urban area has led to C storage loss as several green spaces and areas of agricultural land were transformed into built-up land. A study done for Addis Ababa, Ethiopia, by Abdo and Satyaprakash (2021) [53] also stated that the conversion of most of the LULC classes into built-up land and transport will lead to a reduced area of green space in the city, causing a subsequent drop in C storage for the future simulated years 2028 and 2038.

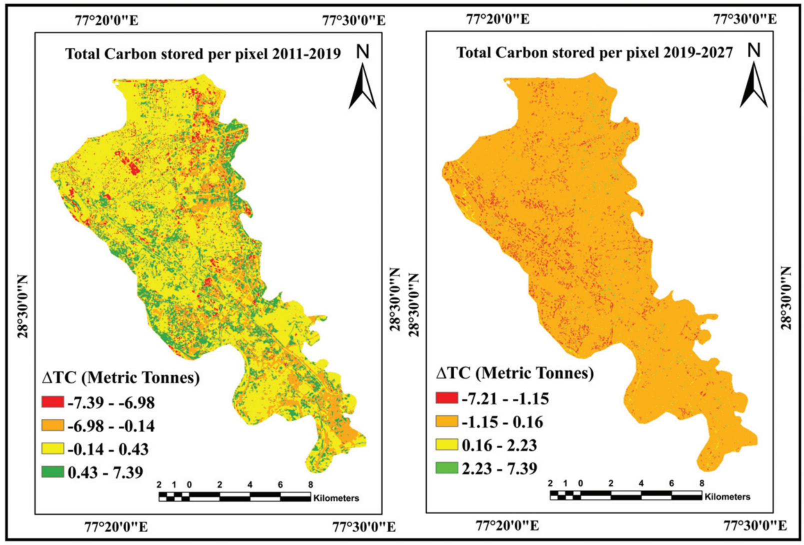

Figure 7. Total carbon stored per pixel—2011–2019 and 2019–2027.

4.5. Economic Valuation of Carbon Gain/Loss

The monetary contribution of C sequestered in the observed (2011–2019) and projected (2019–2027) time periods of Noida city are illustrated in Table 8. The findings reveal a monetary gain of 17.53 million dollars at a 3% discount rate due to C sequestered by urban green areas during the period 2011–2019 (Figure 8). Because of the augmentation in the C stock in the city from 2011 to 2019, this economic gain was observed. For the simulated period (2019–2027), a loss of 4.46 million dollars was recorded due to the predicted decline in vegetation (Figure 8). If the UGS of the city are not sustained and augmented, there will be a net loss of economic value derived from C stored. A similar study carried out in Jiroft plain, Iran, reported US$ 36 million as the cost of damage due to the loss of C stored between 2019 and 2045 [54].

Table 8. Total economic costs due to C sequestration.

Years	NPV (Million Dollars)
2011–2019	17.53
2019–2027	−4.46

4.6. Future Scope of the Work

This study could be further expanded by incorporating additional carbon pools such as Soil Organic Carbon (SOC) and dead organic matter, providing a more comprehensive carbon budget. Enhancing the model validation through field data integration and high-resolution remote sensing would improve the accuracy. Extending the temporal scope to include long-term projections and climate change scenarios would offer insights into sustainable urban planning. Integrating the findings with urban policies, developing decision support systems, and evaluating the socio-economic benefits of carbon sequestration could guide sustainable development. Additionally, using advanced machine learning models and real-time monitoring technologies would further refine the predictions and support urban sustainability efforts.

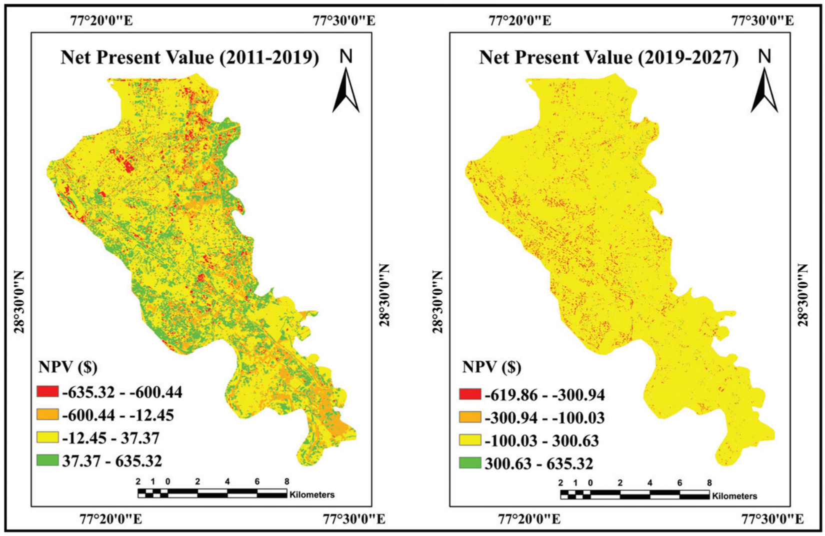

Figure 8. Net Present Value–2011–2019 and 2019–2027.

5. Conclusions

Economic development and government policies are the two primary propelling causes of the LULC changes observed in Noida. The overall direction of urban growth is towards the northeast and south of the city, along which the density has also increased in the northern part. Areas under built-up land and vegetation increased between 2011 and 2019, while agricultural areas decreased substantially. Over the past twenty years, the city has undergone rapid conurbation. As per the development plan for city for the year 2021, 6055 hectares of area were recommended for urban development, with 61.61 percent of the total land stated to have already been developed. The building of the Metro line, the Buddha International Circuit, the FNG and Yamuna Expressway, the National Dalit Memorial, as well as other residential and commercial buildings, are a few examples [94].

Since the InVEST model facilitated the simulation, forecast, and monetary evaluation of the possible impacts of urbanisation on the city's C-storage capacity at different levels, such models are becoming more and more popular. To assess current and future climatic consequences at the city scale, it is essential to comprehend the magnitude and spatio-temporal distribution of carbon dioxide (CO_2) equivalents. This study exemplifies a bottom-up approach or regional analyses, which can be replicated for all other urban cities experiencing significant landscape alterations. Estimates of the C storage of urban areas provide past records to serve as a baseline and a precursor to study future changes, and therefore, more such city-scale analyses are required rather than just depending on the national estimates. The monetary valuation of ecosystem services like C sequestration by urban green areas helps us to comprehend the social and environmental importance of these functions of nature. The estimation and mapping of the changing pattern of the C sequestration potential of urban green spaces is a crucial tool that can aid in devising prudent management strategies of urban green spaces, augmenting cities' capacities to store C and manage climate change.

The findings of this study highlight a momentous transformation of the land cover in the city, and if appropriate actions are not taken as soon as possible, this could result in the elimination of all available space for vegetation. This would, as a result of a decrease in C sequestration, further exacerbate a variety of environmental, socioeconomic, and public health issues, and would also prevent the city from growing in a sustainable way. As a result, those responsible for formulating public policy and urban planning should collaborate to determine how land should be utilised for future sustainable urban development. Such key data about the amount and distribution of C stored within existing urban vegetation, the portion of C sequestered or lost over time, and its relationship with the changing urban landscape are vital for such decisions.

Author Contributions: R.S.: Conceptualization, Writing—original draft. L.P.: Resources, Data curation, Writing—review & editing. P.B.: Writing—review & editing. M.K.: Data curation, Writing—review & editing, Supervision. V.N.M.: Data curation, Writing—review & editing. D.K.: Writing—review & editing, Supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author as it is part of on-going Ph.D. work.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhuang, Q.; Shao, Z.; Gong, J.; Li, D.; Huang, X.; Zhang, Y.; Xiaodi, X.; Dang, C.; Chen, J.; Altan, O.; et al. Modeling Carbon Storage in Urban Vegetation: Progress, Challenges, and Opportunities. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *114*, 103058. [CrossRef]
2. Allen, C.; Metternicht, G.; Wiedmann, T. National Pathways to the Sustainable Development Goals (SDGs): A Comparative Review of Scenario Modelling Tools. *Environ. Sci. Policy* **2016**, *66*, 199–207. [CrossRef]
3. IPCC. *IPCC on Mitigation of Climate Change*; Cambridge University Press: Cambridge, UK, 2014.
4. Gurney, K.R.; Liang, J.; Roest, G.; Song, Y.; Mueller, K.; Lauvaux, T. Under-reporting of Greenhouse Gas Emissions in US Cities. *Nat. Commun.* **2021**, *12*, 553. [CrossRef]
5. Kinnunen, A.; Talvitie, I.; Ottelin, J.; Heinonen, J.; Junnila, S. Carbon Sequestration and Storage Potential of Urban Residential Environment–A Review. *Sustain. Cities Soc.* **2022**, *84*, 104027. [CrossRef]
6. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Eds.; National Greenhouse Gas Inventories Programme, IGES: Tokyo, Japan, 2006; pp. 1–20.
7. Scharlemann, J.P.; Tanner, E.V.; Hiederer, R.; Kapos, V. Global Soil Carbon: Understanding and Managing the Largest Terrestrial Carbon Pool. *Carbon Manag.* **2014**, *5*, 81–91. [CrossRef]
8. Vashum, K.T.; Jayakumar, S. Methods to Estimate Above-Ground Biomass and Carbon Stock in Natural Forests—A Review. *J. Ecosyst. Ecogr.* **2012**, *2*, 116. [CrossRef]
9. Helen, J.M.; Gasparatos, A. Land Use Change, Carbon Stocks and Tree Species Diversity in Green Spaces of a Secondary City in Myanmar, Pyin Oo Lwin. *PLoS ONE* **2019**, *14*, e0225331. [CrossRef]
10. Behera, S.K.; Mishra, S.; Sahu, N.; Manika, N.; Singh, S.N.; Anto, S.; Kumar, R.; Husain, R.; Verma, A.K.; Pandey, N. Assessment of Carbon Sequestration Potential of Tropical Tree Species for Urban Forestry in India. *Ecol. Eng.* **2022**, *181*, 106692. [CrossRef]
11. Shadman, S.; Khalid, P.A.; Hanafiah, M.M.; Koyande, A.K.; Islam, M.A.; Bhuiyan, S.A.; Woon, K.S.; Show, P.L. The Carbon Sequestration Potential of Urban Public Parks of Densely Populated Cities to Improve Environmental Sustainability. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102064. [CrossRef]
12. Uniyal, S.; Purohit, S.; Chaurasia, K.; Rao, S.S.; Amminedu, E. Quantification of Carbon Sequestration by Urban Forest Using Landsat 8 OLI and Machine Learning Algorithms in Jodhpur, India. *Urban For. Urban Green.* **2022**, *67*, 127445. [CrossRef]
13. Ren, Z.; Zheng, H.; He, X.; Zhang, D.; Shen, G.; Zhai, C. Changes in Spatio-Temporal Patterns of Urban Forest and Its Above-Ground Carbon Storage: Implication for Urban CO2 Emissions Mitigation under China's Rapid Urban Expansion and Greening. *Environ. Int.* **2019**, *129*, 438–450. [CrossRef]
14. Crisp, D.; Dolman, H.; Tanhua, T.; McKinley, G.A.; Hauck, J.; Bastos, A.; Sitch, S.; Eggleston, S.; Aich, V. How Well Do We Understand the Land-Ocean-Atmosphere Carbon Cycle? *Rev. Geophys.* **2022**, *60*, e2021RG000736. [CrossRef]
15. Zhang, F.; Xu, N.; Wang, C.; Wu, F.; Chu, X. Effects of Land Use and Land Cover Change on Carbon Sequestration and Adaptive Management in Shanghai, China. *Phys. Chem. Earth, Parts A/B/C* **2020**, *120*, 102948. [CrossRef]
16. Chen, Y.; Yue, W.; Liu, X.; Zhang, L.; Chen, Y. Multi-Scenario Simulation for the Consequence of Urban Expansion on Carbon Storage: A Comparative Study in Central Asian Republics. *Land* **2021**, *10*, 608. [CrossRef]
17. Tang, X.; Zhao, X.; Bai, Y.; Tang, Z.; Wang, W.; Zhao, Y.; Wan, H.; Xie, Z.; Shi, X.; Wu, B. Carbon Pools in China's Terrestrial Ecosystems: New Estimates Based on an Intensive Field Survey. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 4021–4026. [CrossRef]
18. Raciti, S.M.; Hutyra, L.R.; Newell, J.D. Mapping Carbon Storage in Urban Trees with Multi-Source Remote Sensing Data: Relationships between Biomass, Land Use, and Demographics in Boston Neighborhoods. *Sci. Total Environ.* **2014**, *500*, 72–83. [CrossRef]
19. Myeong, S.; Nowak, D.J.; Duggin, M.J. A Temporal Analysis of Urban Forest Carbon Storage Using Remote Sensing. *Remote Sens. Environ.* **2006**, *101*, 277–282. [CrossRef]
20. Goudriaan, J. Atmospheric CO_2, Global Carbon Fluxes and the Biosphere. In *Theoretical Production Ecology: Reflections and Prospects*; Pudoc: Wageningen, The Netherlands, 1990; pp. 17–40.

21. Zhang, C.; Tian, H.; Chen, G.; Chappelka, A.; Xu, X.; Ren, W.; Hui, D.; Liu, M.; Lu, C.; Pan, S.; et al. Impacts of Urbanization on Carbon Balance in Terrestrial Ecosystems of the Southern United States. *Environ. Pollut.* **2012**, *164*, 89–101. [CrossRef] [PubMed]
22. Gao, Z.Q.; Liu, J.Y.; Cao, M.K.; Li, K.R.; Tao, B. Impacts of Land-Use and Climate Changes on Ecosystem Productivity and Carbon Cycle in the Cropping-Grazing Transitional Zone in China. *Sci. China Ser. D-Earth Sci.* **2005**, *48*, 1479–1491. [CrossRef]
23. Yu, X.; Wang, H.; Cai, W.; Han, Y. Analysis of Urban Forest Carbon Sequestration Capacity: A Case Study of Zengdu, Suizhou. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *42*, W7. [CrossRef]
24. Ma, J.; Li, X.; Baoquan, J.; Liu, X.; Li, T.; Zhang, W.; Liu, W. Spatial Variation Analysis of Urban Forest Vegetation Carbon Storage and Sequestration in Built-Up Areas of Beijing Based on i-Tree Eco and Kriging. *Urban For. Urban Green.* **2021**, *66*, 127413. [CrossRef]
25. Song, P.; Kim, G.; Mayer, A.; He, R.; Tian, G. Assessing the Ecosystem Services of Various Types of Urban Green Spaces Based on i-Tree Eco. *Sustainability* **2020**, *12*, 1630. [CrossRef]
26. Li, Q.; Zhu, Y.; Zhu, Z. Calculation and Optimization of the Carbon Sink Benefits of Green Space Plants in Residential Areas: A Case Study of Suojin Village in Nanjing. *Sustainability* **2023**, *15*, 607. [CrossRef]
27. Russo, A.; Escobedo, F.J.; Timilsina, N.; Schmitt, A.O.; Varela, S.; Zerbe, S. Assessing Urban Tree Carbon Storage and Sequestration in Bolzano, Italy. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2014**, *10*, 54–70. [CrossRef]
28. Nowak, D.J.; Crane, D.E. Carbon Storage and Sequestration by Urban Trees in the USA. *Environ. Pollut.* **2002**, *116*, 381–389. [CrossRef]
29. Davies, Z.G.; Edmondson, J.L.; Heinemeyer, A.; Leake, J.R.; Gaston, K.J. Mapping an Urban Ecosystem Service: Quantifying Above-Ground Carbon Storage at a City-Wide Scale. *J. Appl. Ecol.* **2011**, *48*, 1125–1134. [CrossRef]
30. Vorster, A.G.; Evangelista, P.H.; Stovall, A.E.; Ex, S. Variability and Uncertainty in Forest Biomass Estimates from the Tree to Landscape Scale: The Role of Allometric Equations. *Carbon Balance Manag.* **2020**, *15*, 8. [CrossRef] [PubMed]
31. Vijayalaxmi, R.S.; Dnyanesh, M.M. Carbon Sequestration Potential of Urban Green Spaces (PMC Gardens) in Pune City, India. *J. Geogr. Environ. Earth Sci. Int.* **2021**, *25*, 22–38. [CrossRef]
32. Lahoti, S.; Lahoti, A.; Joshi, R.K.; Saito, O. Vegetation Structure, Species Composition, and Carbon Sink Potential of Urban Green Spaces in Nagpur City, India. *Land* **2020**, *9*, 107. [CrossRef]
33. Subba, M.; Pala, N.A.; Shukla, G.; Chakravarty, S. Study of the Variability of Home Gardens Influencing Carbon Stock under Sub-Humid Tropical Zone of West Bengal, India. *Indian For.* **2018**, *144*, 60–66.
34. Devi, R. Carbon Storage by Trees in Urban Parks: A Case Study of Jammu, Jammu and Kashmir, India. *Int. J. Adv. Res. Dev.* **2017**, *2*, 250–253.
35. Prabhakar, B.S.; Kumar, M.; Nandini, N. Evaluating the Tree Species Composition and Carbon Sequestration Potential of a Park in Bengaluru. *Int. J. Curr. Res.* **2015**, *7*, 22320–22325.
36. Tripathi, M.; Joshi, H. Carbon Flow in Delhi Urban Forest Ecosystems. *Ann. Biol. Res.* **2015**, *6*, 13–17.
37. Pandya, I.Y.; Salvi, H.; Chahar, O.; Vaghela, N. Quantitative Analysis on Carbon Storage of 25 Valuable Tree Species of Gujarat, Incredible India. *Indian J. Sci. Res.* **2013**, *4*, 137–141.
38. Kiran, G.S.; Kinnary, S. Carbon Sequestration by Urban Trees on Roadsides of Vadodara City. *Int. J. Eng. Sci. Technol.* **2011**, *3*, 3066–3070.
39. Nagendra, H.; Gopal, D. Street Trees in Bangalore: Density, Diversity, Composition and Distribution. *Urban For. Urban Green.* **2010**, *9*, 129–137. [CrossRef]
40. Waran, A.; Patwardhan, A. Urban Carbon Burden of Pune City: A Case Study from India. Master's Thesis, University of Pune, Pune, India, 2001.
41. Sharp, R.; Tallis, H.T.; Ricketts, T.; Guerry, A.D.; Wood, S.A.; Chaplin-Kramer, R.; Nelson, E.; Ennaanay, D.; Wolny, S.; Olwero, N.; et al. *InVEST 3.2.0 User's Guide*; The Natural Capital Project: Stanford, CA, USA, 2015.
42. Kohestani, N.; Rastgar, S.; Heydari, G.; Jouibary, S.S.; Amirnejad, H. Spatiotemporal Modeling of the Value of Carbon Sequestration under Changing Land Use/Land Cover Using InVEST Model: A Case Study of Nour-rud Watershed, Northern Iran. *Environ. Dev. Sustain.* **2023**, *26*, 14477–14505. [CrossRef]
43. Felix, N.B.; Campos, P.C.D.O.; Paz, I.; Marques, M.E.S. Geoprocessing Applied to the Assessment of Carbon Storage and Sequestration in a Brazilian Medium-Sized City. *Sustainability* **2022**, *14*, 8761. [CrossRef]
44. Li, Y.; Liu, Z.; Li, S.; Li, X. Multi-Scenario Simulation Analysis of Land Use and Carbon Storage Changes in Changchun City Based on FLUS and InVEST Model. *Land* **2022**, *11*, 647. [CrossRef]
45. Tao, Y.; Li, F.; Liu, X.; Zhao, D.; Sun, X.; Xu, L. Variation in Ecosystem Services across an Urbanization Gradient: A Study of Terrestrial Carbon Stocks from Changzhou, China. *Ecol. Modell.* **2015**, *318*, 210–216. [CrossRef]
46. Goldstein, J.H.; Caldarone, G.; Duarte, T.K.; Ennaanay, D.; Hannahs, N.; Mendoza, G.; Polasky, S.; Wolny, S.; Daily, G.C. Integrating Ecosystem-Service Tradeoffs into Land-Use Decisions. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 7565–7570. [CrossRef]
47. Nelson, E.; Sander, H.; Hawthorne, P.; Conte, M.; Ennaanay, D.; Wolny, S.; Manson, S.; Polasky, S. Projecting Global Land-Use Change and Its Effect on Ecosystem Service Provision and Biodiversity with Simple Models. *PLoS ONE* **2010**, *5*, e14327. [CrossRef] [PubMed]
48. He, C.; Zhang, D.; Huang, Q.; Zhao, Y. Assessing the Potential Impacts of Urban Expansion on Regional Carbon Storage by Linking the LUSD-Urban and InVEST Models. *Environ. Modell. Softw.* **2016**, *75*, 44–58. [CrossRef]

49. Polasky, S.; Nelson, E.; Pennington, D.; Johnson, K.A. The Impact of Land-Use Change on Ecosystem Services, Biodiversity, and Returns to Landowners: A Case Study in the State of Minnesota. *Environ. Resour. Econ.* **2011**, *48*, 219–242. [CrossRef]
50. Leh, M.D.K.; Matlock, M.D.; Cummings, E.C.; Nalley, L.L. Quantifying and Mapping Multiple Ecosystem Services Change in West Africa. *Agric. Ecosyst. Environ.* **2013**, *165*, 6–18. [CrossRef]
51. Delphin, S.; Escobedo, F.J.; Abd-Elrahman, A.; Cropper, W., Jr. Mapping Potential Carbon and Timber Losses from Hurricanes Using a Decision Tree and Ecosystem Services Driver Model. *J. Environ. Manag.* **2013**, *129*, 599–607. [CrossRef]
52. Liu, S.; Hu, N.; Zhang, J.; Lv, Z. Spatiotemporal Change of Carbon Storage in the Loess Plateau of Northern Shaanxi, Based on the InVEST Model. *Sci. Cold Arid Reg.* **2018**, *10*, 240–250.
53. Abdo, Z.A.; Satyaprakash. Modeling Urban Dynamics and Carbon Sequestration in Addis Ababa, Ethiopia, Using Satellite Images. *Arab. J. Geosci.* **2021**, *14*, 445. [CrossRef]
54. Adelisardou, F.; Zhao, W.; Chow, R.; Mederly, P.; Minkina, T.; Schou, J.S. Spatiotemporal Change Detection of Carbon Storage and Sequestration in an Arid Ecosystem by Integrating Google Earth Engine and InVEST (the Jiroft Plain, Iran). *Int. J. Environ. Sci. Technol.* **2022**, *19*, 5929–5944. [CrossRef]
55. Piyathilake, I.D.U.H.; Udayakumara, E.P.N.; Ranaweera, L.V.; Gunatilake, S.K. Modeling Predictive Assessment of Carbon Storage Using InVEST Model in Uva Province, Sri Lanka. *Model. Earth Syst. Environ.* **2022**, *8*, 2213–2223. [CrossRef]
56. He, Y.; Ma, J.; Zhang, C.; Yang, H. Spatio-temporal evolution and prediction of carbon storage in Guilin based on FLUS and InVEST models. *Remote Sens.* **2023**, *15*, 1445. [CrossRef]
57. Rachid, L.; Elmostafa, A.; Mehdi, M.; Hassan, R. Assessing carbon storage and sequestration benefits of urban greening in Nador City, Morocco, utilizing GIS and the InVEST model. *Sustain. Futures* **2024**, *7*, 100171. [CrossRef]
58. Zafar, Z.; Zubair, M.; Zha, Y.; Mehmood, M.S.; Rehman, A.; Fahd, S.; Nadeem, A.A. Predictive modeling of regional carbon storage dynamics in response to land use/land cover changes: An InVEST-based analysis. *Ecol. Inform.* **2024**, *82*, 102701. [CrossRef]
59. Gupta, S.; Nainwal, A.; Anand, S.; Singh, S. Valuation of Carbon Sequestration in Bidhalna Microwatershed, Uttarakhand, India Using InVEST Model. *Int. J. Adv. Earth Environ. Sci.* **2017**, *5*, 10–15.
60. Chacko, S.; Ravichandran, C.; Vairavel, S.; Mathew, J. Employing Measures of Spatial Distribution of Carbon Storage in Periyar Tiger Reserve, Southern Western Ghats, India. *J. Geovis. Spat. Anal.* **2019**, *3*, 1. [CrossRef]
61. Babbar, D.; Areendran, G.; Sahana, M.; Sarma, K.; Raj, K.; Sivadas, A. Assessment and Prediction of Carbon Sequestration Using Markov Chain and InVEST Model in Sariska Tiger Reserve, India. *J. Clean. Prod.* **2021**, *278*, 123–333. [CrossRef]
62. Bera, B.; Bhattacharjee, S.; Sengupta, N.; Shit, P.K.; Adhikary, P.P.; Sengupta, D.; Saha, S. Significant Reduction of Carbon Stocks and Changes of Ecosystem Service Valuation of Indian Sundarban. *Sci. Rep.* **2022**, *12*, 7809. [CrossRef]
63. Verma, P.; Siddiqui, A.R.; Mourya, N.K.; Devi, A.R. Forest carbon sequestration mapping and economic quantification infusing MLPnn-Markov Chain and InVEST carbon model in askot wildlife sanctuary, Western Himalaya. *Ecol. Inform.* **2024**, *79*, 102428. [CrossRef]
64. Wei, Z.; Wu, S.; Yan, X.; Zhou, S. Density and stability of soil organic carbon beneath impervious surfaces in urban areas. *PLoS ONE* **2014**, *9*, e109380. [CrossRef]
65. Piotrowska-Długosz, A.; Charzyński, P. The impact of the soil sealing degree on microbial biomass, enzymatic activity, and physicochemical properties in the Ekranic Technosols of Toruń (Poland). *J. Soils Sediments* **2015**, *15*, 47–59. [CrossRef]
66. Vasenev, V.I.; Van Oudenhoven, A.P.E.; Romzaykina, O.N.; Hajiaghaeva, R.A. The Ecological Functions and Ecosystem Services of Urban and Technogenic Soils: From Theory to Practice (A Review). *Eurasian Soil Sci.* **2018**, *51*, 1119–1132. [CrossRef]
67. Chien, S.C.; Krumins, J.A. Natural versus urban global soil organic carbon stocks: A meta-analysis. *Sci. Total Environ.* **2022**, *807*, 150999. [CrossRef]
68. WRB. 2022. Available online: https://wrb.isric.org/files/WRB_fourth_edition_2022-12-18.pdf (accessed on 10 August 2024).
69. Mishra, B.B. Indian System of Soil Classification: A way Forward. *Agric. Res. Technol. Open Access J.* **2016**, *3*, 555606. [CrossRef]
70. Brahma, B.; Nath, A.J.; Deb, C.; Sileshi, G.W.; Sahoo, U.K.; Das, A.K. A Critical Review of Forest Biomass Estimation Equations in India. *Trees For. People* **2021**, *5*, 100098. [CrossRef]
71. Ghosh, A.; Sharma, R.; Joshi, P.K. Random Forest Classification of Urban Landscape Using Landsat Archive and Ancillary Data: Combining Seasonal Maps with Decision Level Fusion. *Appl. Geogr.* **2014**, *48*, 31–41. [CrossRef]
72. Amani, M.; Ghorbanian, A.; Ahmadi, S.A.; Kakooei, M.; Moghimi, A.; Mirmazloumi, S.M.; Brisco, B. Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A Comprehensive Review. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2020**, *13*, 5326–5350. [CrossRef]
73. Breiman, L. Random Forests. *Mach. Learn.* **2001**, *45*, 5–32. [CrossRef]
74. Kumari, M.; Sarma, K.; Sharma, R. Predicting Spatial and Decadal LULC Changes in the Singrauli District of Madhya Pradesh Through Artificial Neural Network Models Using Geospatial Technology. *J. Indian Soc. Remote Sens.* **2022**, *51*, 519–530. [CrossRef]
75. Tallis, H.T.; Ricketts, T.; Guerry, A.D.; Wood, S.A.; Sharp, R.; Nelson, E.; Ennaanay, D.; Wolny, S.; Olwero, N.; Vigerstol, K.; et al. *InVEST 2.6.0 User's Guide*; The Natural Capital Project: Stanford, CA, USA, 2013.
76. Xu, L.; Zhang, J.; Hu, P.; Zhang, W.; Xiao, L.; Ye, Y.; Xiao, D.; Zhao, J.; Xiao, J.; Wang, K. Bedrock outcrops weakly promote rather than inhibit soil carbon sequestration after vegetation restoration. *Sci. Total Environ.* **2023**, *858*, 159470. [CrossRef]
77. Forest Survey of India (FSI). *Carbon Stock in India's Forests*; Ministry of Environment, Forest & Climate Change, Government of India: Dehradun, India, 2011.

78. Forest Survey of India (FSI). *India State of Forest Report*; Ministry of Environment, Forest & Climate Change, Government of India: Dehradun, India, 2019.
79. Ricke, K.; Drouet, L.; Caldeira, K.; Tavoni, M. Country-Level Social Cost of Carbon. *Nat. Clim. Chang.* **2018**, *8*, 895–900. [CrossRef]
80. Kaur, S.; Babbar, D.; Sarif, O.; Ghatak, A.; Jaafari, A. Assessment of carbon sequestration using InVEST model in Delhi, India. In *Conservation, Management and Monitoring of Forest Resources in India*; Springer International Publishing: Cham, Switzerland, 2022; pp. 33–56.
81. Jo, H.K. Impacts of Urban Greenspace on Offsetting Carbon Emissions for Middle Korea. *J. Environ. Manag.* **2002**, *64*, 115–126. [CrossRef] [PubMed]
82. Chaparro, L.; Terradas, J. *Ecological Services of Urban Forest in Barcelona*; Institut Municipal de Parcs i Jardins Ajuntament de Barcelona, Àrea de Medi Ambient: Barcelona, Spain, 2009.
83. Strohbach, M.W.; Haase, D. Above-Ground Carbon Storage by Urban Trees in Leipzig, Germany: Analysis of Patterns in a European City. *Landsc. Urban Plan.* **2012**, *104*, 95–104. [CrossRef]
84. Skole, D.L.; Samek, J.H.; Dieng, M.; Mbow, C. The Contribution of Trees Outside of Forests to Landscape Carbon and Climate Change Mitigation in West Africa. *Forests* **2021**, *12*, 1652. [CrossRef]
85. Pasher, J.; McGovern, M.; Khoury, M.; Duffe, J. Assessing Carbon Storage and Sequestration by Canada's Urban Forests Using High Resolution Earth Observation Data. *Urban For. Urban Green.* **2014**, *13*, 484–494. [CrossRef]
86. Zhao, M.; Kong, Z.H.; Escobedo, F.J.; Gao, J. Impacts of Urban Forests on Offsetting Carbon Emissions from Industrial Energy Use in Hangzhou, China. *J. Environ. Manag.* **2010**, *91*, 807–814. [CrossRef] [PubMed]
87. Kändler, G.; Adler, P.; Hellbach, A. Wie viel Kohlenstoff speichern Stadtbäume? Eine Fallstudie am Beispiel der Stadt Karlsruhe [How Much Carbon Is Stored by Urban Trees? A Case Study from the City of Karlsruhe]. *FVA-Einblick* **2011**, *2*, 7–10. (In German)
88. Liu, C.; Li, X. Carbon Storage and Sequestration by Urban Forests in Shenyang, China. *Urban For. Urban Green.* **2012**, *11*, 121–128. [CrossRef]
89. Yang, J.; McBride, J.; Zhou, J.; Sun, Z. The Urban Forest in Beijing and Its Role in Air Pollution Reduction. *Urban For. Urban Green.* **2005**, *3*, 65–78. [CrossRef]
90. Majumdar, T.; Selvan, T. Carbon Storage in Trees of Urban and Peri-Urban Forests of Agartala, Tripura. *IAETSD J. Adv. Res. Appl. Sci.* **2018**, *5*, 715–731.
91. McPherson, E.G.; Xiao, Q.F.; Aguaron, E. A New Approach to Quantify and Map Carbon Stored, Sequestered and Emissions Avoided by Urban Forests. *Landsc. Urban Plan.* **2013**, *120*, 70–84. [CrossRef]
92. Nero, B.F.; Callo-Concha, D.; Anning, A.; Denich, M. Urban Green Spaces Enhance Climate Change Mitigation in Cities of the Global South: The Case of Kumasi, Ghana. *Procedia Eng.* **2017**, *198*, 69–83. [CrossRef]
93. Jiang, W.; Deng, Y.; Tang, Z.; Lei, X.; Chen, Z. Modelling the Potential Impacts of Urban Ecosystem Changes on Carbon Storage under Different Scenarios by Linking the CLUE-S and the InVEST Models. *Ecol. Modell.* **2017**, *345*, 30–40. [CrossRef]
94. Sharma, R.; Pradhan, L.; Kumari, M.; Bhattacharya, P. Assessing Urban Heat Islands and Thermal Comfort in Noida City Using Geospatial Technology. *Urban Clim.* **2021**, *35*, 100751. [CrossRef]

land

Article

Mapping and Assessing Effective Participatory Planning Processes for Urban Green Spaces in Aotearoa New Zealand's Diverse Communities

Yiwen Cui [1], Morten Gjerde [2] and Bruno Marques [1,*]

[1] Te Kura Waihanga-School of Architecture, Victoria University of Wellington, Wellington 6012, New Zealand; yiwen.cui@vuw.ac.nz
[2] Department of Architecture & Planning, Norwegian University of Science & Technology, 7491 Trondheim, Norway; morten.gjerde@ntnu.no
* Correspondence: bruno.marques@vuw.ac.nz; Tel.: +64-027-805-1331

Abstract: The multicultural landscape of Aotearoa New Zealand presents a rich tapestry of diversity and community needs, underscoring an imperative for inclusive participatory planning processes. This paper presents findings from an investigation of the challenges and opportunities inherent in community engagement initiatives, particularly within the context of New Zealand's major ethnic groups, including New Zealand European, Māori, Chinese, and Pasifika. Drawing from the importance of community participation in reshaping public open spaces, this research addressed the gap in understanding which participatory planning processes are most effective across diverse cultural groups. To investigate the effectiveness of various approaches to community engagement, this research involved focus groups from the Wellington suburbs of Newtown and Porirua, utilising both on-site and online meetings. The findings identify the most effective participation processes for planning public open spaces in relation to each ethnicity. Correlations between participant preferences and their unique cultural backgrounds were assessed. In addition, the least effective participation methods along with several relatively effective participation methods are discussed. By highlighting engagement methods that can foster inclusivity, equity, and a sense of community, this research advances a collective goal of building a more cohesive and effective society for all its inhabitants.

Keywords: participatory planning process; effectiveness; focus groups; cultural diversity

Citation: Cui, Y.; Gjerde, M.; Marques, B. Mapping and Assessing Effective Participatory Planning Processes for Urban Green Spaces in Aotearoa New Zealand's Diverse Communities. *Land* **2024**, *13*, 1412. https://doi.org/10.3390/land13091412

Academic Editor: Kenneth R. Young

Received: 20 July 2024
Revised: 26 August 2024
Accepted: 27 August 2024
Published: 1 September 2024

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

1. Introduction

Since the signing of the Treaty of Waitangi in 1840, Aotearoa New Zealand has witnessed a remarkable transformation into a society with multiple ethnic groups, characterised by a rich tapestry of diversity and community needs. This multicultural landscape brings with it a multitude of perspectives, traditions, and experiences, contributing to the vibrant mosaic of New Zealand's social community fabric [1].

Community participation has become increasingly important as cities have become more ethnically diverse and racially divided. The opportunity to participate in civic life has been identified as a core human need, essential to the communities' sense of place [2]. People rely on public open spaces for social interaction as well as access and connection to the surrounding communities [3]. The goal of participatory planning is to incorporate the public perspective into the planning process and actual design of the public open space [4].

This equally aligns with earlier research, which argues that implementing high-quality participatory planning of public open spaces is a fundamental approach to embracing this cultural diversity, cultivating a deeper connection to community, and encouraging a higher sense of community for the major ethnic groups in Aotearoa New Zealand [5].

However, in terms of practical experience in community participatory planning, this growing cultural diversity and difference can create challenges for the participation processes. For example, a change undertaken to suit the needs of one cultural ethnicity could be seen as threatening or otherwise inappropriate for another. In addition, even though community members using public open spaces often possess the knowledge and physical proximity to those resources, they are frequently not included in transformation and maintenance processes. Due to these kinds of cultural conflicts and obstacles to participation, community engagement in planning can make it difficult to reach consensus within a limited time. These barriers have significantly restricted the ability of community participation in planning to address the challenge of conflicts and differences [6].

On the path to dealing with such issues and difficulties with community participation, there exists a notable gap in understanding the effectiveness of community participation processes among the major ethnic groups in Aotearoa New Zealand. In this context, the most effective participatory planning processes should be explored and discovered not only to better recognise and resolve these cultural differences and conflicts but also to "provide creative ways for interaction and negotiation of competing visions, interests, values, and identities" [6] (p. 312). While community engagement initiatives are essential for promoting inclusivity and empowering diverse communities, there is limited empirical evidence on how these processes operate within specific cultural contexts and whether they adequately address the needs and preferences of different ethnic groups. By addressing this knowledge gap, this research explores evidence-based strategies for enhancing the inclusivity, equity, and efficacy of community engagement initiatives across diverse cultural landscapes, thereby fostering a more effective, cohesive, and resilient society in Aotearoa New Zealand (Figure 1).

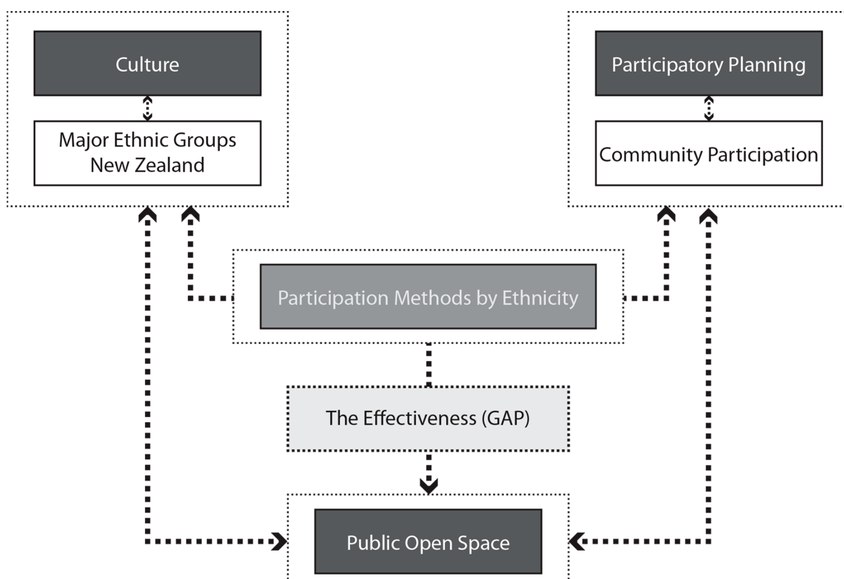

Figure 1. Gap and opportunity.

This study seeks to address the following research question: "what differences are there for New Zealand European, Māori, Chinese, and Pasifika (also called Pacific Peoples) community members in the process of participatory planning for community public open space?" By investigating the unique participation processes of these ethnic groups, this research aims to uncover how cultural and community dynamics shape engagement in public open space planning. Through this inquiry, the outcomes of this study help to explore and discover insights that can inform more effective participatory planning strategies.

2. Literature Review

Participatory planning is an "attitude about a force for change in the creation and management of environments for people" [7] (p. 12). The goal of participatory planning is to cut across the differences that can develop between professional advisers and the public, and to encourage different perspectives on the planning and design process of public open spaces [8]. Most often, it is the community projects dealing with public open spaces that citizens can feel directly influencing their daily lives.

In the 1960s, community participation created opportunities for direct involvement of the public in planning their closely related physical environment. Following this wave of movement, communities started to offer design and planning processes or methods to enable community members to join in and implement their own planning projects and goals [7].

2.1. Community Participation and Public Open Space

Public open space functions as "a place to provide opportunities for any kinds of recreational activities promote social interaction" [9] (p. 311). To create a successful public open space, participation of the community in the decision-making process is very important as the community members are the primary stakeholders and can help ensure the success of the public open space [9]. In addition, participatory planning and design serve as the foremost approach in addressing community concerns, and it has remained a vital method for local communities to actively shape the creation of public open spaces [10]. The involvement of community members at every stage, from setting goals to designing programs and projects, represents a wide range of community interests and can result in a system that is better equipped to address the diverse needs of the community.

However, community participation has experienced an increasing number of reassessments in the literature on planning. According to Mark Francis, "community participation has become firmly institutionalised, it also has become more of a tool for defending exclusionary, conservative principles than for promoting social justice and ecological vision" [11] (p. 61). Jean Hillier also discussed the institutionalisation that results from the inefficiency and formalisation of the participation process. This institutionalisation, whether intentional or unintentional, tends to favour particular groups' participation while discouraging or even preventing others from participating [12]. These obstacles have significantly limited the capacity of community participation in planning to effectively tackle conflicts and differences, which confirms that the breadth and significance of community participation in planning have progressively diminished [6].

In the past few decades, methods of conflict resolution and consensus building have been developed to deal with different perspectives and interests. However, some of these methods have also been discovered to be inadequate, especially when interactions and negotiations happened during a formalised participation process [6]. Firstly, the formalised process can "deflect discussion of value issues, to control difficult participants, and to manipulate participative processes" [13] (p. 177). Secondly, the formalised process creates obstacles for planners when they are confronted with issues related to cultural diversities and nuances [14,15]. The array of cultural diversities and nuances poses a challenge to participatory planning when participation is constrained by rigid formal rules and procedures detached from the social processes and dynamics within communities [6].

2.2. Community Participation Methods—General

As an alternative to the formalised participation process in community planning, an informal participation process that can offer a broader range of more effective opportunities for engagement, dialogue, and interactions that help overcome the institutional barriers and address the community and cultural differences should be considered [6]. The existing literature related to community participation in planning has certified the concept and influence of the informal participation process [16,17]. For instance, informal participation such as walking tours, design games, and social events could provide opportunities and catalysts for building mutual trust and a better understanding of the design ideas [17].

Given the strong evidence in the literature, it is clear that informal community participation processes can "significantly contribute to the effectiveness of participatory planning at the community level" [6] (p. 303). Community participation processes should effectively incorporate the available resources and engagement techniques. Techniques such as walking guides, surveys, and small focus groups are a few options for future design. With an appropriate participation process or method, people could have an active role in the community planning process, and multi-stakeholders may also be involved in finding practical, locally based, and long-term solutions to community regeneration and conservation programs. When community members participate in creating their own environment, they will have a feeling of control. And this is the only way their needs and values can be considered [4].

The following methods can be utilised to encourage and guide public participation.

2.2.1. Participatory Mapping

Participatory mapping "engages community members in geographic mapping of their community's assets, needs, opportunities and other considerations to inform the community planning process" [18] (p. 31). It has surfaced as a crucial tool in community planning, enabling the identification and communication of development needs, and it has also gained acknowledgment as a method to foster social change [19].

Participatory mapping is an approach to creating maps, aimed at highlighting the connections between a location and its communities by employing cartographic techniques [19]. An ordinary form of participatory mapping comprises an aerial map or the conventional base map of a community for potential participants to write or draw on with magic markers or stickers. These maps might include labels for street names, public open spaces, key locations, and other features that help participants locate themselves and can inform the particular purpose of the mapping activity [20].

2.2.2. Guided Tours

Guided tours "are among the emerging mobile methods that emphasise the importance of the evaluator being present and in motion with the participant, to make data collection a shared journey" [21] (p. 1383). It involves pre-planned tours through a neighbourhood area aimed at familiarising participants with current conditions and can be utilised to explore potential improvements in the area [18]. The planner or designer accompanies the participant, actively listening and posing questions to encourage dialogue and grasp the participant's viewpoints [21]. Moreover, guided tours can serve as optional perspectives for exploring the issues under investigation [22].

A guided tour gathers potential community members with different backgrounds, enhancing the project's awareness and interests, which could bring increased engagement and satisfaction and finally result in a consensus solution [22].

2.2.3. Focus Groups

Focus groups are "a small group of people guided by a facilitator to provide feedback on a given topic, which has applications throughout social-science research and marketing campaigns as well as in community planning" [18] (p. 37). A focus group stands out as a distinct type of gathering due to its specific purpose, size, composition, and methodology. It is utilised to gain deeper insights into people's sentiments or thoughts regarding an issue, idea, product, or service [23].

A typical focus group has four to six participants, who are selected representatives from community associations, community-based organisations, or direct community members living in that area who have certain characteristics in common that relate to the topic of the focus group [23]. Because of the smaller size of the sessions, focus groups are always considered to be cost effective and time efficient.

2.2.4. 3D Visualisation

3D visualisation "allows stakeholders to see the potential results, development and design projects through computer modelling and photographic imaging" [18] (p. 39). Utilising 3D visualisation tools with a high level of interactivity should be pivotal in fostering effective communication, which can lead to increased participation in dialogue processes [24].

This 3D technique provides opportunities for all stakeholders to check the existing conditions and the proposed planning more straightforwardly. It can also provide different options for design and planning as all related images and design can be digitally manipulated so that planners or community members can better evaluate various possibilities and scenarios [18]. Compared to the two-dimensional plans, 3D visualisation allows community members to visualise directly and accurately what the proposed design or planning will look like.

2.2.5. Interactive Planning

Interactive planning "taps into the public's memories and emotions of place through building models for a community's built environment from found, recycled objects" [18] (p. 40).

Regardless of professional background and skills, interactive planning provides a great opportunity to help community members translate abstract and conceptual planning into actual physical items and forms. These physical models represent the focus site, including the general streets, landmarks, and other key features. This platform is supposed to be reorganised and manipulated by community members, which creates a better understanding of the built environment and the proposed planning [18]. People will have the experience and accessibility to building possible solutions rather than merely talking about them. This interaction between community members and planners can also facilitate the communication and relationship between them, which will also encourage potential participation in the project [25].

2.2.6. Visual Preference Surveys

Visual preference surveys (VPSs) enable community members to evaluate physical images of natural and built environments [18]. The VPSs help community members "envision design alternatives in ways that words, maps, and other communications media cannot" [26] (p. 271). They can be used as a tool for identifying values and setting goals for community planning and have been proven to help develop a consensus between developers and the public [27].

The VPS requires participants to review and assess a sequence of slides. Participants examine each slide and assign it a score based on their immediate reaction or preference to the image, whether they find it appealing and whether they believe it is suitable for their community [18]. The most common way to assess preferences is with ratings on a Likert scale. The result of the survey stands for the collective preferences of the participants [26].

2.3. Community Participation Methods—Local

2.3.1. Hui—Māori

In Māori Indigenous culture, hui "refers to an occasion where people come together to renew old friendships, to celebrate, debate, tell stories and to listen to", which would be hosted precisely in the local marae (meeting grounds) [28] (p. 5).

At the present time, the contemporary hui can be held in a number of public venues or locations other than the local marae, including the public hall at schools or universities, the city council, and the conference room. All of those places can be appropriate if proper cultural protocols are adopted [29].

In the modern use of hui, an essential element is the ceremonial form that establishes the context for the ensuing discussion [28]. Moreover, hui has gained growing recognition as a culturally suitable method for individuals or institutions to interact with Māori and to gain a high level of trust and respect [29].

2.3.2. Talanoa—Pasifika

From the perspective of Pasifika, talanoa is a word that promotes open discussion and respect among each other [28]. It is a combination of two terms. Tala means telling stories or talking and noa represents heartfelt communication without concealment [30].

In Pasifika communities, talanoa occurs within the groups when Pasifika are trying to reach a consensus and agreement on a new idea or issue. It also creates a friendly and informal environment so Pasifika community members can freely communicate without hesitations or concerns [30]. It is a good opportunity to reconnect with the Pasifika community members and promote their interactions. Therefore, talanoa "enables participation in the way that the participant wishes, sets the connections within the group which promotes good relations, delves deep to uncover rich data and build consensus within the group around a topic" [31] (p. 539).

3. Method

To answer the research question, this study adopted the qualitative research method of focus groups, which was perfectly matched and useful for exploring, discovering, and identifying people's experiences of participation processes in community planning. It also helped to understand not only what they think but also how they think and why they think that way.

3.1. Ethical Issues

Throughout all focus group sessions, the authors took precautions to ensure that engagement with respondents was ethically and culturally appropriate. To build the relationship of trust and connection, the authors were advised by local residents' associations, community centres, and city councils. A person from the liaison group was appointed to work with the researchers to ensure the collected data could be well protected throughout the project, in line with cultural and Treaty of Waitangi protocols.

3.2. Participants

A total number of 30 participants were recruited for this research, including New Zealand European, Māori, Chinese, and Pasifika (Table 1) ethnic groups. As snowball and purposive sampling methods were employed, local community associations and church parishes as well as city councils provided tremendous help in spreading information and recruiting potential participants. These entities have built and continue to maintain close relationships with local residents and the local Māori tribe, including Ngāti Toa. This assisted with the recruitment of Māori participants and ensured appropriate adherence to protocols.

Table 1. Number of participants.

	Newtown		**Porirua**			
Ethnicity	NZEU	Chinese	NZEU	Māori	Chinese	Pasifika
Number of participants	5	4	4	3	5	9

As this research is meant to gain an understanding of people's experiences of participatory planning, and the researcher typically seeks more in-depth insights about how people in each ethnic group perceive its effectiveness, a small focus group is best suited as it is "easier to recruit and host, and they [small groups] are more comfortable for participants" [23] (p. 74). While the focus groups may be relatively small, the deliberate recruitment strategy aimed to capture a wide array of viewpoints within each ethnic group, strengthening the validity and generalisability of the findings. This also allows the researcher to focus on creating a conducive environment for meaningful dialogue and discussions as well as a safe environment for those who are participating [32].

In addition, the recruitment process for the small focus groups involved collaboration with local community associations, which assisted in disseminating information and identifying potential participants who met this study's criteria. While specific demographic details cannot be disclosed due to ethical considerations, efforts were made to ensure a diverse range of perspectives within each ethnic group and to enhance the richness of the data and support the credibility of the findings [33]. Participants were recruited from various backgrounds and included individuals with varying levels of community involvement, professional experiences, and affiliations with aforementioned organisations. The snowball sampling method can be effective in reaching hidden populations or those with varying degrees of engagement, provided that recruitment is guided by a conscious effort to maximise diversity [34].

Recruiting Māori participants is generally more challenging due to factors such as geographical dispersion and smaller community size and differing levels of engagement with this research. Moreover, Māori communities often have specific cultural protocols and ethical considerations that need to be respected when conducting research. Key principles, such as whakapapa (relationships) and mana (authority and dignity), underscore the importance of building trust, engaging with the community in a culturally respectful manner, and ensuring that the research process is aligned with Māori values [35]. This type of engagement can be time-consuming, as it involves establishing genuine relationships and ensuring that the research is conducted in a way that benefits the community. These factors can naturally limit the number of participants, as the focus is on quality of engagement and ethical rigor rather than quantity. Finally, during the same period of this research, the global spread of the pandemic also created some obstacles, which both physically and virtually limited the number of potential participants.

3.3. Focus Group Sessions

Table 2 presents the general description of all focus group sessions. Each focus group was arranged exclusively for participants from that ethnic community. As people prefer to reveal "sensitive information when they felt they were in a safe, comfortable place with people like themselves" [23] (p. 6). Focus group sessions were being held in locations where community members are more familiar and comfortable, such as the Community and Cultural Centre in Newtown and the Cultural Centre and City Hub in Porirua.

Table 2. General description of focus groups.

Community	Ethnic Group	Location	Number
Newtown	New Zealand European	Newtown Community Hall	3
		Newtown Community Centre	2
	Chinese	Online	4
Porirua	New Zealand European	Online	4
	Māori	Online	3
	Chinese	Online	3
		Online	2
	Pasifika	City Hub, Porirua	2
		Online	7

Initially, the focus group sessions were organised and hosted on-site. However, due to the COVID-19 pandemic outbreak, the remaining focus group sessions changed to online meetings through a digital visual communication platform.

3.4. Coding and Transcription

To ensure better and continuous communication during the conversation and avoid losing data, it was necessary to audio record the whole focus group session using a recorder and then transcribe the content into an abridged transcript without irrelevant or redundant parts.

The transcriptions were coded and entered into NVivo 12.0, a software commonly used for qualitative research to document and sort focus group recordings and transcriptions.

Each participant was assigned a letter code to protect their identity (Table 3). Moreover, the six numbers in Table 4 represent the six participation methods concluded from the literature.

Table 3. Description of the focus group letter-codes.

	Community	Ethnicity	Participant Code Sample
Focus Group	Newtown	New Zealand European Chinese	FG-NT-EU-A (A-E) FG-NT-CH-B (A-D)
	Porirua	New Zealand European Māori Chinese Pasifika	FG-PR-EU-C (A-D) FG-PR-MA-B (A-C) FG-PR-CH-E (A-E) FG-PR-PA-F (A-I)

Table 4. Participation methods coding.

Coding	Participation Methods	Abbreviation
No. 1	Participatory Mapping	PM
No. 2	Guided Tour	GT
No. 3	Focus Group	FG
No. 4	3D Visualisation	3D
No. 5	Interactive Planning	IP
No. 6	Visual Preference Survey	VPS

Numbers 1 to 3 represent the prioritisation of the effective participation methods selected by the participants during the focus groups. Participants rated the effectiveness of those methods, from No. 1—extremely effective to No. 3—slightly effective (Table 5).

Table 5. Scale of effectiveness.

Coding	Scale
①	Extremely Effective
②	Moderately Effective
③	Slightly Effective

4. Data Analysis and Discussion

The general procedure of the analysis is shown below (Figure 2). The cross-case analysis and discussions were focused on targeting ethnic groups separately, including New Zealand European, Māori, Chinese, and Pasifika, in terms of the comments and feedback provided by the participants. The experience and effectiveness of the community participation process were examined, and the reasons for selecting each of the focused ethnic groups were analysed and discussed. Moreover, cultural background and influence, two of the most critical concepts in this research, were analysed and discussed in conjunction with the highly effective participation methods selected by the targeting ethnic groups.

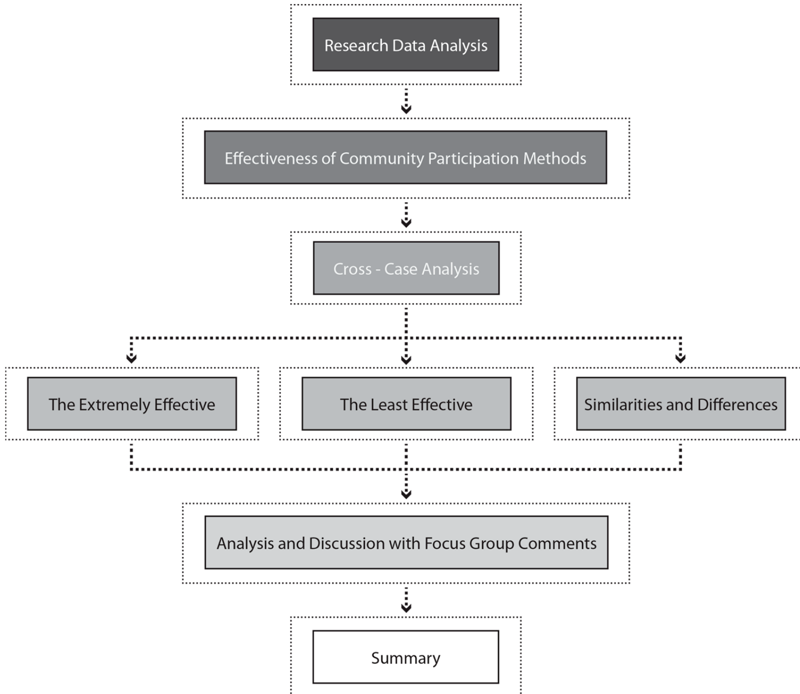

Figure 2. Data analysis procedure.

4.1. Extremely Effective Participation Methods by Ethnicity

In Table 6, for the selections of the extremely effective methods, the majority of New Zealand Europeans chose No. 4, the 3D visualisation; a great number of Māori selected No. 2, the guided tour; most Chinese chose No. 6, the visual preference survey, and numerous Pasifika chose No. 2, the guided tour.

Table 6. The most effective participation method for each of the four ethnic groups in the study.

Ethnic Group	PM	GT	FG	3D	IP	VPS	Hui	Talanoa
New Zealand European				①				
Māori		①					☆	
Chinese						①		
Pasifika		①						☆

In addition, all Māori participants chose hui as the specific method, which should be placed at the start of the participation process. All Pasifika participants selected talanoa as an extra method that was unique and appropriate to their ethnicity.

4.2. Cross-Case Analysis and Discussions by Culture

The relationship between cultural influence and the selection of the effective participation method by the corresponding ethnic groups is analysed and summarised in this section.

4.2.1. 3D Visualisation for New Zealand European

From the focus group discussions with New Zealand Europeans, the selection of the 3D visualisation refers to the latest 3D technology employed in the participation project.

According to modern Western philosophy, the different ways people relate to nature can be characterised as (1) humans being influenced by nature, (2) reacting to nature, and (3) finding ways to tame elements of nature through new technologies to solve problems [36]. New technologies have played an important role since the Industrial Revolution by promoting the harmonious relationship between humans and nature. So, from the perspective of human's relationships with nature, Western culture pays particular attention to and prefers developing and implementing science and technology.

This focus and preference are expressed as the following viewpoints in pursuing 3D technology from focus groups. Firstly, from the point of the visualised perspective provided by 3D visualisation, the following point was made:

> *For 3D visualisation, I like your idea of doing it for 3 dimensional rather than as flat mapping.* (FG-PR-EU-A)

The participants emphasised that it provides a better visualisation in comparison to other methods, which is a key point from the literature that this three-dimensional visualisation allows participants to directly and accurately visualise the proposed design [37].

Secondly, from the point of convenience and time efficiency, the following points were made:

> *It's easier for me to interpret than the 2D plan.* (FG-NT-EU-A)

> *It's also convenient for me to see that in my own time and my own space. I can do this quickly and I can spend as much time as I want. So, it's time efficient.* (FG-NT-EU-A)

> *The 3D visualisation is the least amount of effort on my part. It's great that I could still be involved, but little effort.* (FG-NT-EU-D)

The feedback is matched with the existing literature that the 3D visualisation method is a more straightforward way and will simplify the design process and settle with realistic and accurate images [24,37]. What is more, the participants confirmed this factor of 3D visualisation, making the participation process convenient and time-efficient with the least amount of effort [24].

In summary, the focus group discussions with participants from New Zealand Europeans underscore a deep-seated connection between their preferences for new technology and the broader cultural backgrounds. This interest is rooted in the historical context of the Western world's dominance in technological innovation; participants expressed a natural affinity for methods that leverage advancements in technology to enhance efficiency [38]. This inclination was also reflected in the focus group discussions, where participants were keenly interested in utilising the latest technologies, such as 3D visualisation, to engage in participatory processes.

4.2.2. Guided Tour and Hui for Māori

Culturally speaking, it is necessary and appropriate to organise hui at the beginning of the whole participation process, as this will be an essential procedure for building trust and respect for individuals or institutions to engage with Māori [29,39]. The Māori participants also proposed that getting to know everyone and the potential projects is an important part of relationship-building. Hui is one of the extremely important procedures when engaging with Māori as an outsider:

> *So, bring them from the early stages, being able to introduce yourself, and then be able to take their engagement throughout the whole process is really key.* (FG-PR-MA-A)

> *That can be as simple as just an initial hui for everyone to get to know everyone and what projects are happening.* (FG-PR-MA-C)

Hui is a Māori term and a special ceremony targeting and providing opportunities for Māori community members to be involved and freely present their different opinions on potential projects with respect [28,40]. According to the feedback provided during the sessions, hui is an essential process at the beginning to start making connections and trust so that they can better work together and collaborate on good ideas:

> *I think a big part comes to that is the relationship building or the connections, especially hui at the start.* (FG-PR-MA-B)

> *You get a sense of transparency. A sense that you are being informed. People will feel more confident that you are being told everything you need to know.* (FG-PR-MA-A)

Māori also have a unique perception and affinity with the land [41,42]. Most of the Māori participants believed that their understanding, feeling, and attachment to this land are much more profound when compared with other ethnic groups nowadays:

> *Our understanding of the land is a lot deeper than anyone else. As you know, historically, it was their land before colonisation.* (FG-PR-MA-A)

This shared journey of a guided tour provides them with an excellent opportunity to experience and feel the land so closely, to put forward their specific concerns, and to exchange valuable ideas when walking with designers [18,21].

> *For Māori, that guided tour helps you to get a feel of reality, so that you are trusting your own eyes in your own sensibilities.* (FG-PR-MA-B)

> *When you are out there, you can capture those holistic relationships and you can capture those cultural landscapes.* (FG-PR-MA-C)

From a Māori perspective, the connection between humans and ecosystems is critical, believing that the selection of a guided tour promotes a deeper connection to mana whenua (territorial rights over the land) [41]. It is understood that Māori need to establish a solid and intimate connection with whenua (the land), which leads to the practical selection of the guided tour. In addition, the Māori worldview acknowledges that all living things and natural resources are connected, and this holistic interaction between humans and nature can also significantly impact their health and wellbeing [39,41,43].

This reveals another reason for selecting the guided tour as the highly effective participation method, which is conducive to strengthening the connection to the land and potentially increasing their mana (spiritual power):

> *Because Māori has a lot more connection with the land. When we start to touch the whenua, that always has a direct impact on the people.* (FG-PR-MA-A)

> *So, their main concern is around their people, their iwi and their mana whenua, and what the impacts there are going to be on them.* (FG-PR-MA-B)

To conclude, this selection of the extremely effective participation method for Māori is based on their historical and cultural background, which is closely related to and concentrated on the connection to the land and the better health and well-being associated with establishing this intimate connection and relationship.

4.2.3. Visual Preference Survey for Chinese

Historically speaking, the community in China is based on the kinship network, and the family members live geographically close to each other so that they can take care of each other when necessary. This means that the ancient Chinese culture developed from collective cooperation to ensure their survival in nature [44]. This collectivist spirit has been ingrained in Chinese culture for centuries, ensuring survival and prosperity amidst natural challenges.

Even in the contemporary era, this collectivist culture persists. Before 1978, society and communities were rooted in a traditional Chinese collectivistic culture. People at that time lived in public housing provided by their workplace or employment unit. Under this unique sociocultural background, their collectivist values existed within social ties and kinship all in the neighbourhood atmosphere of the public housing. After 1978, even though the old employment units were largely dissolved, and the kinship networks considerably changed because of the new economic system, the traditional culture still exists, and people living in the new communities are also working collectively to address their own community needs and issues [45].

The focus on collectivism is reflected explicitly in the following perspectives on their selection of the visual preference survey. Firstly, from the perspective of multiple options and solutions for the potential project, the following points were made:

> *I chose No. 6, because we are not professionals, and No. 6 will help broaden our horizons and make a more diversified choice.* (FG-NT-CH-D)

> *For the images in the VPS, they are all based on the mature program.* (FG-PR-CH-D)

A point of view from the literature corroborated the argument above. This method aims to make community members evaluate the images or slides of natural and built environments to help identify value and set goals for community planning [18].

Secondly, from the perspective that this method provides collective contributions for the potential projects, the following points were made:

> *VPS can grab people's opinions as a collective preference so that the designers can help us in a scientific way. We need to collect most people's opinions.* (FG-NT-CH-A)

> *The results from the VPS will be a collective view from all the participants in the community.* (FG-PR-CH-E)

The collective response value on the images or slides represents the collective consciousness of the whole of the surveyed participants, which will stand for a collective understanding and will be consistent with the preference of the whole community [46].

The focus group discussions with participants from Chinese backgrounds illuminate a profound connection between their participation preferences and the cultural value of collectivism. Rooted in their traditions, Chinese culture places a strong emphasis on collective action. This cultural tradition is reflected in the focus group discussions, where participants prioritised methods that foster collective contributions and consensus formation. Participants expressed a preference for this VPS approach that allows for the consideration of diverse perspectives and the pooling of collective wisdom to inform decision-making processes. The emphasis on collective decision-making resonates with their broader cultural values of cooperation and community cohesion within the Chinese community. Moreover, participants viewed this VPS as an opportunity to harness the collective consciousness of the community and ensure that decisions align with the shared values and preferences of the group.

From ancient to contemporary perspectives, Chinese culture continuously emphasises the spirit of collectivism. From this point of view, their selection of the highly effective participation method of the visual preference survey and the keyword of collectivism mentioned above can be interconnected.

4.2.4. Guided Tour and Talanoa for Pasifika

Talanoa is normally "a traditional Pacific reciprocating interaction, which is driven by common interest, regard for respectfulness, and is conducted mainly face to face" [47] (p. 31). All participants proposed that this is an essential and required method, which should be not only placed at the beginning of the community participation process but also is a continuous process to go through for the whole project:

> *This process would probably be the first consultation for our pacific communities, primarily because we would like to do things together communally.* (FG-PR-PA-A)

> *I think talanoa is not a one-off process, it is a continuous process that need to ensure it is on-going.* (FG-PR-PA-I)

For Pasifika, in both formal and informal settings, the talanoa process can be adopted and used for all of these situations, and it is suitable for enabling the potential participants to communicate [28]. Therefore, talanoa enables the participation of community members and helps promote good relationships within a permissive environment [31]:

> *It's what brings the Pacific people together.* (FG-PR-PA-I)
>
> *For me, the talanoa is based on the trust. If you are hosting the talanoa very successful, and we will follow the process and the pace.* (FG-PR-PA-C)

This permissive environment allows all participants to share their views to make sure all voices are heard rather than that all views are presented [28]. This environment also promotes open discussions and respect among participants, which is echoed by the aim of talanoa to facilitate inclusivity by providing comfortable environments and encouraging discussions [31]:

> *The talanoa process is the most respectful way of being able to talk freely in a space for everyone.* (FG-PR-PA-D)
>
> *The talanoa is an opportunity to have a free discussion in a safe place. It's an inclusive of everyone, and we are running the meeting equally.* (FG-PR-PA-F)

This inclusivity creates a healthy social relationship, which is vital to Pacific peoples' wellbeing and a sense of community in life [47], and this relationship should be maintained through positive interactions with community members. What is more, the Pasifika self is meaningful only in relation to others, and this relational self as a source of mental wellbeing is balanced with the physical interactions with families and community members [48]:

> *Because we are very interactive people, we like to feel each other and we are reciprocal learners. Like we learn from you and you learn from us.* (FG-PR-PA-F)
>
> *Everyone from different backgrounds will come and interact. Then you will see the other one's ideas and you will see their mana.* (FG-PR-PA-G)

Their selection of guided tours provides excellent opportunities for Pasifika participants to interact on-site. This is consistent with the literature about the importance of social interaction, which encourages people's involvement. In Pasifika communities, social and community interactions are perceived to be a valuable aspect of Pasifika culture and an opportunity to contribute to and improve their own communities [49].

In conclusion, for Pasifika, from the relationship to self and others and the emphasis on talanoa, the selection of the highly effective participation method is mainly connected to interactivity, which is closely related to the Pasifika cultural background and strongly supported by the literature.

4.3. The Least Effective Participation Method

After analysing the highly effective participation methods, Table 7 identifies that No. 1, participatory mapping, is the least selected and, thus, the least effective method for all ethnic groups studied in this research. The main reasons are that most of the community members are not professionals, making it difficult for them to understand and read two-dimensional mapping within that short period of time during the participation sessions:

Table 7. Frequency of the selected effective methods by all ethnic groups.

Ethnic Group	PM	GT	FG	3D	IP	VPS
All Ethnic Groups	4	20	12	23	13	18

> *I may be struggle to read the 2D maps.* (FG-PR-EU-D)
>
> *I think the 2-dimensional mapping will be not straightforward and easy for us. Most of us are not professionals, and reading the maps require some knowledge.* (FG-NT-CH-C)
>
> *We are not the professionals, when you see a map, it's just a map.* (FG-PR-PA-H)

> *For PM, I really don't understand how to read maps. And I have been to a session like that. When I was looking at it and it meant nothing to me.* (FG-PR-PA-F)

The use of participatory mapping generally requires a facilitator with a professional background who will introduce the project and the required activities, including how to review the maps and the instructions for marking and labelling [18]. As such, this approach was selected as the least effective participation method.

4.4. Series of the Relatively Effective Participation Methods

Other than the most and least effective participation methods for targeting ethnic groups, different combinations of relatively effective participation methods are identified (Table 8). This analysis helped us to understand the common areas of overlap and the areas of difference when it comes to the series of effective participation methods by ethnicity.

Table 8. Mapping the most to the slightly effective participatory method by ethnicity. The coding is described above in Table 5.

Ethnic Group	PM	GT	FG	3D	IP	VPS	Hui	Talanoa
New Zealand European		③		①		②		
Māori		①	②			③	☆	
Chinese		③		②		①		
Pasifika		①		③	②			☆

For the preferred method across all ethnic groups, it is clear that No. 2, guided tour, is the most common selection as one of the effective participation methods. For future potential projects, if some or all these ethnic groups are involved, this approach is suggested to be applied to the targeting of groups of diverse people, which will also make the potential projects and participation process more effective.

For New Zealand Europeans and Chinese, all three selections for effective participation methods are exactly the same. This means that, without considering the different rankings of effective participation methods, the choices of the community participation methods adopted and utilised for these two ethnic groups are similar. Based on this result, if future projects include these two ethnic groups, designers should adopt and focus on the same methods but with different priorities.

The other two preferences for Māori, except for the guided tour, are the focus group and the visual preference survey. For Pasifika, the other two choices are 3D visualisation and interactive planning. Based on the generalisations above, when targeting Māori and Pasifika, those effective participation combinations and strategies should be adopted and utilised according to their own selections.

The rankings shown in Table 8 deepen our understanding of the effectiveness of the different participation methods examined in this study. This also suggests that reliance only on the extremely effective participation method alone cannot solve all potential problems. Instead, it can be suggested that a series or combination of relatively effective participation methods can be more effective.

4.5. Implications

Practitioners and policy makers are encouraged to tailor community participation processes to specific ethnic backgrounds and cultural preferences, enhancing engagement effectiveness by aligning methods with unique needs and inclinations.

For practice, recognising the inclination of New Zealand Europeans towards technology and innovation, practitioners can employ digital tools and platforms to facilitate participation and communication. Emphasising Indigenous history, land connections, and wellbeing can enhance Māori engagement while acknowledging the collective nature of Chinese culture can promote group-based participation methods that emphasise collaboration and consensus building. Leveraging interactive methods can align with the cultural preference for interactivity among Pasifika communities, fostering effective engagement through hands-on involvement and dialogue. Adopting a flexible approach by combining different participation methods tailored to specific ethnic groups can enhance overall effectiveness. Practitioners should consider a mix of practical methods that cater to diverse preferences and needs within communities.

Regarding policy, it is essential to integrate cultural values into community engagement frameworks. This includes allocating resources to support tailored participation methods and ensuring that policies reflect the diverse needs and preferences of communities. By incorporating cultural considerations into policy design and implementation, governments can promote inclusivity, equity, and meaningful engagement across diverse populations.

5. Conclusions

This research has examined community members' experiences of participatory design processes and explored the effectiveness of these methods in relation to their ethnic and cultural backgrounds.

The findings have primarily been organised according to ethnic groupings and further analysed in the context of the socio-cultural literature in order to identify possible reasons underlying people's preferences. The cross-case analysis indicated that the four ethnic groups each have specific preferences for methods for participating in community planning of public open spaces.

The cultural relationships and background for the selections were also explored through the focus group data. Focus group findings indicate the importance of the role of culture in the selection of the most effective community participation methods by targeting ethnic groups: (1) for New Zealand Europeans, their selection of the highly effective participation method is a representation of their cultural viewpoint and pursuit toward new technology and innovation; (2) for Māori, their selection of the highly effective participation method is closely related with their Indigenous history, connections to the land, and the distinctive pursuit of health and wellbeing; (3) for Chinese, their selection of the most effective method and their cultural element of collectivism are interconnected; and (4) for Pasifika, their selection of the highly effective method is connected to their cultural component of interactivity.

From a broader point of view, the results are consistent with previous research and knowledge on participatory design as a tool for community engagement. This emphasises the importance of culturally sensitive methods and stresses the significance of understanding cultural context, to effectively engage with diverse populations [4,50]. On a specific level, other studies found that Māori values and the connection to nature influence their community engagement practices, which aligns with this study where Indigenous cultural practices are central to the selection of effective participation methods [51,52].

The findings also reveal similarities and differences in the selections of all the targeted ethnic groups, including the least effective participation method and a different series of relatively effective participation methods. For the least effective participation method, findings highlight that participatory mapping is selected as the least effective community participation method for all four ethnic groups in this research. Generally speaking, this method is standard for designers but is not necessarily applicable to non-professional community members. While participatory mapping is generally and traditionally recognised as an effective tool in community planning [19,20], this study found it to be the least effective across all ethnic groups. This divergence could be contextualised by considering the specific characteristics of the targeted ethnic groups or the unique nature of the public spaces involved. This also highlights the need to explore and discover contemporary versions of participatory mapping that are culturally adaptive and technologically advanced, ensuring they are relevant and effective in diverse community settings. For the series of relatively effective participation methods, it is suggested that different combinations and series of participation methods should be embraced for different ethnic groups.

This research introduced the effectiveness of community participation methods to fill the gap by providing community members with different ethnic backgrounds the opportunity to engage in the planning of public open spaces effectively. In addition, this research allowed for different strategies to occur in relation to ethnicity, which complements the existing participation process.

6. Limitations

Some limitations emerged as a result of this research.

First, for the focus groups, some sessions took place using an online meeting platform, which limited the interactions or communications among participants. More on-site focus group sessions may help encourage communications and provide additional information to make the interpretation more accurate. At the same time, increasing the sample size for focus group sessions may enable a better understanding of participation methods in relation to different ethnic groups.

Second, because of the time limitation and the COVID pandemic, some potential project types were cancelled, such as an urban renewal project. Adding different project types in different regions may increase the reliability of the research results.

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

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Acknowledgments: We are grateful to the local residents' association and city council in Newtown and Porirua in New Zealand for the help and organisation of focus groups. We thank the participants in those communities for their comments and valuable discussions regarding participatory planning processes.

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

References

1. Thompson, K. A Sense of Place and Identity in Aotearoa New Zealand. In Proceedings of the Textile Society of America Symposium, Santa Fe, New Mexico, 19–23 September 2000; pp. 179–184.
2. Low, S.; Taplin, D.; Scheld, S. *Rethinking Urban Parks: Public Space and Cultural Diversity*; The University of Texas Press: Austin, TX, USA, 2005.
3. Gehl, J. *Life between Buildings: Using Public Space*; Island Press: Washington, DC, USA, 2011.
4. Sanoff, H. *Community Participation Methods in Design and Planning*; Landsc Urban Plan; John Wiley & Sons: Hoboken, NJ, USA, 2000; Volume 50, pp. 1–288.
5. Cui, Y.; Gjerde, M.; Marques, B. Encouraging sense of community in Aotearoa New Zealand: Exploring the role of community participation in public open space planning. *Cities Health* **2023**, *8*, 566–575. [CrossRef]
6. Hou, J.; Kinoshita, I. Bridging Community Differences through Informal Processes: Reexamining Participatory Planning in Seattle and Matsudo. *J. Plan. Educ. Res.* **2007**, *26*, 301–314. [CrossRef]
7. Sanoff, H. Multiple Views of Participatory Design. *J. Fac. Archit.* **2006**, *23*, 11–21. [CrossRef]
8. Cilliers, E.J.; Timmermans, W. The importance of creative participatory planning in the public place-making process. *Environ. Plann B Plann Des.* **2014**, *41*, 413–429. [CrossRef]
9. Shuib, K.B.; Hashim, H.; Nasir, N.A.M. Community Participation Strategies in Planning for Urban Parks. *Procedia Soc. Behav. Sci.* **2015**, *168*, 311–320. [CrossRef]
10. Hou, J.; Rios, M. Community-Driven Place Making: The Social Practice of Participatory Design in the Making of Union Point Park. *J. Archit. Educ.* **2003**, *57*, 19–27. [CrossRef]
11. Francis, M. Proactive Practice: Visionary Thought and Participatory Action in Environmental Design. *Places* **1999**, *12*, 60–68.
12. Hillier, J. Beyond Confused Noise: Ideas Toward Communicative Procedural Justice. *J. Plan. Educ. Res.* **1998**, *18*, 14–24. [CrossRef]
13. Lowry, K.; Adler, P.; Milner, N. Participating the Public: Group Process, Politics, and Planning. *J. Plan. Educ. Res.* **1997**, *16*, 177–187. [CrossRef]

14. Briggs, X.d.S. Doing Democracy Up-Close: Culture, Power, and Communication in Community Building. *J. Plan. Educ. Res.* **1998**, *18*, 1–13. [CrossRef]
15. Schaller, S.; Modan, G. Contesting Public Space and Citizenships: Implications for Neighborhood Business Improvement Districts. *J. Plan. Educ. Res.* **2005**, *24*, 394–407. [CrossRef]
16. Hester, R. Landstyles and Lifescapes: 12 Steps to Community Development. *Landsc. Archit.* **1985**, *75*, 78–85.
17. Sampson, R.J. What "Community" Supplies. In *Urban Problems and Community Development*; Ferguson, R.F., Dickens, W.T., Eds.; Brookings Institution Press: Washington, DC, USA, 1999; pp. 241–292.
18. Davis, D.; Moore, C.N.; Wright, M.; Zykofsky, P. *Participation Tools for Better Community Planning*; Local Government Commission, the California Endowment: Sacramento, CA, USA, 2013.
19. Cochrane, L.; Corbett, J. Participatory Mapping. In *Handbook of Communication for Development and Social Change*; Servaes, J., Ed.; Springer: Singapore, 2020; pp. 705–713.
20. Perkins, C. Community Mapping. *Cart. J.* **2007**, *44*, 127–137. [CrossRef]
21. Balbale, S.; Locatelli, S.; LaVela, S. Through Their Eyes: Lessons Learned Using Participatory Methods in Health Care Quality Improvement Projects. *Qual. Health Res.* **2016**, *26*, 1382–1392. [CrossRef] [PubMed]
22. Bezova, K.; Azara, I. Generating and Sustaining Value Through Guided Tour Experiences' Co-Creation at Heritage Visitor Attractions. *Tour. Plan. Dev.* **2021**, *18*, 226–244. [CrossRef]
23. Krueger, R.A.; Casey, M.A. *Focus Groups: A Practical Guide for Applied Research*; Sage Publications Inc.: Newbury Park, CA, USA, 2015.
24. Billger, M.; Thuvander, L.; Wästberg, B.S. In search of visualization challenges: The development and implementation of visualization tools for supporting dialogue in urban planning processes. *Environ. Plan. B Urban Anal. City Sci.* **2017**, *44*, 1012–1035. [CrossRef]
25. Rojas, J.; Kamp, J. *Dream Play Build: Hands-On Community Engagement for Enduring Spaces and Places*; Island Press: Washington, DC, USA, 2022.
26. Ewing, R. Using a Visual Preference Survey in Transit Design. *Public Work Manag. Policy* **2001**, *5*, 270–280. [CrossRef]
27. Noland, R.B.; Weiner, M.D.; Gao, D.; Cook, M.P.; Nelessen, A. Eye-tracking technology; visual preference surveys, and urban design: Preliminary evidence of an effective methodology. *J. Urban Int. Res. Placemaking Urban Sustain.* **2017**, *10*, 98–110. [CrossRef]
28. Robinson, D.; Robinson, K. *"Pacific Ways" of Talk: Hui and Talanoa*; New Zealand Institute of Economic Research (NZIER): Wellington, New Zealand, 2005; Volume 36.
29. O'Sullivan, J.; Mills, C. The Māori Cultural Institution of Hui: When Meeting Means More Than a Meeting. *Commun. J. N. Z.* **2009**, *10*, 18–39.
30. Halapua, S. *Talanoa Process: The Case of Fiji*; East West Centre: Honolulu, HI, USA, 2002.
31. Vaka, S.; Brannelly, T.; Huntington, A. Getting to the Heart of the Story: Using Talanoa to Explore Pacific Mental Health. *Issues Ment. Health Nurs.* **2016**, *37*, 537–544. [CrossRef]
32. Morgan, D. *Focus Groups as Qualitative Research*; SAGE Publications Inc.: Newbury Park, CA, USA, 1997. [CrossRef]
33. Flick, U. *An Introduction to Qualitative Research*, 5th ed.; Sage Publications Ltd.: Newbury Park, CA, USA, 2014.
34. Wronski, L. Nonprobability Sampling. In *SAGE Research Methods Foundations*; Atkinson, P., Delamont, S., Cernat, A., Sakshaug, J.W., Williams, R.A., Eds.; SAGE Publications Ltd.: Newbury Park, CA, USA, 2020.
35. Hudson, M.; Milne, M.; Reynolds, P.; Russell, K.; Smith, B. *Te Ara Tika: Guidelines for Māori Research Ethics: A Framework for Researchers and Ethics Committee Members*; Health Research Council of New Zealand: Auckland, New Zealand, 2010.
36. Chen, X.; Wu, J. Sustainable landscape architecture: Implications of the Chinese philosophy of "unity of man with nature" and beyond. *Landsc. Ecol.* **2009**, *24*, 1015–1026. [CrossRef]
37. Wu, H.; He, Z.; Gong, J. A virtual globe-based 3D visualization and interactive framework for public participation in urban planning processes. *Comput. Environ. Urban Syst.* **2010**, *34*, 291–298. [CrossRef]
38. Stearns, P.N. *The Industrial Revolution in World History*; Taylor & Francis Group: Oxfordshire, UK, 2021.
39. Marques, B.; Grabasch, G.; McIntosh, J. Fostering Landscape Identity Through Participatory Design with Indigenous Cultures of Australia and Aotearoa/New Zealand. *Space Cult.* **2018**, *24*, 37–52. [CrossRef]
40. Salmond, A. *Hui: A Study of Māori Ceremonial Gatherings*; Penguin Group (NZ): New York, NY, USA, 2009.
41. Harmsworth, G.; Awatere, S. Indigenous Māori Knowledge and Perspectives of Ecosystems. In *Ecosystem Services in New Zealand—Conditions and Trends*; Manaaki Whenua Press: Lincoln, New Zealand, 2013; pp. 274–286.
42. Smith, P.M. *A Concise History of New Zealand*; Cambridge University Press: Cambridge, UK, 2012.
43. Marques, B.; McIntosh, J.; Hatton, W. Haumanu ipukarea, ki uta ki tai: (Re)connecting to landscape and reviving the sense of belonging for health and wellbeing. *Cities Health* **2018**, *2*, 82–90. [CrossRef]
44. Chui, R.C.F. Transnationalism and Migration: Chinese Migrants in New Zealand. *Global Asia J.* **2008**. Paper 4. Available online: https://digitalcommons.pace.edu/cgi/viewcontent.cgi?article=1004&context=global_asia_journal (accessed on 1 July 2008).
45. Gaubatz, P. New Public Space in Urban China: Fewer Walls, More Malls in Beijing, Shanghai and Xining. *China Perspect.* **2008**, *4*, 72–83. [CrossRef]
46. Nelessen, A.C. *Community Visioning for Place Making: A Guide to Visual Preference Surveys for Successful Urban Evolution*; Taylor & Francis Group: Oxfordshire, UK, 2021.

47. Mila, K. Not Another New Zealand-Born Identity Crisis: Well-being and the Politics of Belonging. In *Pacific Identities and Well-Being: Cross-Cultural Perspectives*; Agee, M.N., McIntosh, T., Culbertson, P., Makasiale, C.O., Eds.; Taylor & Francis Group: Oxfordshire, UK, 2012; Chapter 2; pp. 27–45.
48. Tamasese, K.; Peteru, C.; Waldegrave, C.; Busch, A. Ole Taeao Afua, the new morning: A qualitative investigation into Samoan perspectives on mental health and culturally appropriate services. *Aust. N. Z. J. Psychiatry* **2005**, *39*, 300–309. [CrossRef]
49. Gordon, B.; Sauni, P.; Tuagalu, C.; Hodis, F. *Sport and Recreation in New Zealand Pasifika Communities*; Victoria University: Wellington, New Zealand, 2010.
50. Madanipour, A. Public Spaces of European Cities. *Nord. J. Archit. Res.* **2005**, 7–16.
51. Durie, M. *Whaiora, Māori Health Development*, 2nd ed.; Oxford University Press: Oxford, UK, 1998.
52. Marques, B.; Freeman, C.; Carter, L.; Zari, M.P. Conceptualising Therapeutic Environments through Culture, Indigenous Knowledge and Landscape for Health and Well-Being. *Sustainability* **2021**, *13*, 9125. [CrossRef]

land

MDPI

Article

Comprehensive Ecological Functional Zoning: A Data-Driven Approach for Sustainable Land Use and Environmental Management—A Case Study in Shenzhen, China

Yu Li [1,*], Fenghao Zhang [2], Ruifan Li [2], Hongbing Yu [1,2], Yao Chen [3] and Han Yu [1,4,*]

[1] Guangdong-Hong Kong-Macao Greater Bay Area Environmental Technology Research Center, Shenzhen Research Institute of Nankai University, Shenzhen 518063, China; hongbingyu1130@sina.com
[2] College of Environmental Science and Engineering, Nankai University, Tianjin 300350, China
[3] Shenzhen Lightsun Analysis and Testing Center Co., Ltd., Shenzhen 518029, China
[4] Department of Water Resources Engineering, Lund University, 22100 Lund, Sweden
* Correspondence: liyuhydro@nankai.edu.cn (Y.L.); yhh20212022@gmail.com (H.Y.)

Abstract: A comprehensive approach to ecological functional zoning in the Shenzhen region of China is presented in this study. Through the integration of advanced geospatial analysis tools, multiple data sources, and sophisticated statistical techniques, different ecological functions have been identified and categorized based on a comprehensive set of indicators and spatial analysis techniques. The three-level zoning framework established in this study offers policymakers, urban planners, and environmental managers a nuanced understanding of the region's environmental characteristics, and highlights areas of ecological significance that warrant special attention and protection. It has been demonstrated that the data-driven approach to ecological functional zoning is effective in delineating distinct ecological zones within the study area. This study's findings carry significant implications for future land use planning, conservation efforts, and sustainable development practices in the Shenzhen region. In essence, this study contributes to the broader discourse on ecological planning and environmental management by providing a systematic and data-driven approach to delineating ecological functional zones in urbanizing regions.

Keywords: ecological functional zoning; data-driven approach; sustainable land use; environmental management

Citation: Li, Y.; Zhang, F.; Li, R.; Yu, H.; Chen, Y.; Yu, H. Comprehensive Ecological Functional Zoning: A Data-Driven Approach for Sustainable Land Use and Environmental Management—A Case Study in Shenzhen, China. *Land* **2024**, *13*, 1413. https://doi.org/10.3390/land13091413

Academic Editors: Luca Battisti, Fabrizio Aimar and Federico Cuomo

Received: 26 July 2024
Revised: 28 August 2024
Accepted: 30 August 2024
Published: 2 September 2024

1. Introduction

Ecological functional zoning is a vital endeavor that revolves around the regional ecological environment [1,2]. The interconnectedness and mutual constraints of ecological factors within a region give rise to diverse structures, facilitate various ecological processes, deliver a range of services to humanity, and ultimately shape the regional ecological environment [3,4]. The spatial division or integration of ecological functional regions is based on overarching connectivity, spatial continuity, ecological process similarity and dissimilarity, service function characteristics, and the intensity of human activities.

The origins of ecological zoning can be traced back to 1898, when Merriam conducted a comprehensive classification of biological zones and crop zones in the United States, establishing the foundation for a biological-based ecological zoning approach [5]. In recent years, significant progress has been made in applying remote sensing and machine learning techniques to study land–water interfaces and ecological systems [6–8]. Although many studies have employed machine learning algorithms to classify land cover and plant communities in coastal regions, the focus has primarily been on analyzing individual spatial data layers without exploring the interactions and mutual influences among different layers [9,10]. While notable regional-scale ecological zoning efforts have been undertaken [11,12], these initiatives have mainly concentrated on natural ecological factors with limited consideration for the role of humans within ecosystems [13]. Addressing pressing global challenges such as population growth, resource scarcity, and environmental degradation, ecologists have redirected their attention to ecological zoning, recognizing the limitations of past approaches and acknowledging the vital role and impact of human activities on resource development and environmental conservation [14,15].

Chinese researchers have also made significant contributions to the field of ecological zoning [16–19]. Li's work on ecological sensitivity and ecosystem service functions in Hainan Province, as well as Yang's foundational research on national ecology, exemplify efforts to provide a scientific basis for regional economic development policies, sustainable resource management, and ecological preservation [20,21]. Furthermore, Fu [22] proposed a comprehensive framework for national ecological zoning, dividing the country into 3 ecological zones, 13 ecological regions, and 54 ecological areas, considering ecosystem service functions, sensitivity, and human influences. Hong et al. [23] established an ecological vulnerability assessment indicator system comprising nine elements and twelve indicators, focusing on ecological sensitivity, ecological pressure, and self-resilience. It spatially identifies ecologically vulnerable areas within a highly urbanized region. Highly vulnerable areas, primarily located in the western region and intertwined with urban functional zones, suggest the need for establishing an ecological red line and enforcing stringent controls akin to China's existing ecological protection laws. The Chinese government is vigorously advancing its carbon market and began establishing the national carbon market in December 2017 [24]. The efficiency of market information is a crucial measure of market maturity and is essential for participants to devise trading strategies. As one of the pilot cities, Shenzhen's policies play a significant role in its comprehensive ecological functional zoning [25].

However, there is a lack of research on hierarchical methods for coastal ecosystems and the establishment of comprehensive protection systems at the intersection of highly developed areas and urban environments [26–29]. Liu et al.'s study [30] underscores the complexity of economic development's impact on the environment, highlighting differing trends between production and consumption-related pollutants. It suggests that targeted policies addressing both industrial production and consumption patterns are crucial for achieving sustainable development goals in rapidly urbanizing regions like Shenzhen. Ecological security patterns (ESPs) integrate landscape patterns and ecological processes to enhance ecological connectivity, promoting the coordinated development of social systems and ecosystems [31]. Wang et al. [32] chose townships in the Tacheng Basin, Xinjiang, China, as the basic research units, and established an evaluation index system covering ecological protection, agricultural production, and urban development suitability, and they analyzed them using spatial analysis functions and an exclusive matrix method. An assessment system integrating ecological security and economic development was constructed for evaluating these areas, fully considering drivers such as precipitation, temperature, topography, soil, land use, geological disasters, and landscapes that impact the ecosystem [33]. While previous ecological zoning research has primarily focused on large-scale land and watershed spaces, there are a limited number of comprehensive studies on small to medium-scale urban coastal areas, impeding the development of guiding research results used for reference [34,35].

In conclusion, while ecological zoning and mapping have garnered significant attention and research efforts, there is untapped potential for further exploration and development, particularly in addressing the complex ecological challenges at the intersection of urban and highly developed areas. This calls for a concerted effort to advance ecological zoning research and develop comprehensive protection strategies to ensure the sustainable coexistence of human activities and natural ecosystems. The purpose of this study is to propose the theoretical basis and specific zoning techniques for three-level ecological functional zoning at medium and small scales, and to validate and apply this method in the study area.

2. Methodology

This section introduces a comprehensive three-level framework for regional ecological functional zoning, focusing on the scales of watershed, sub-watershed, and river. To further achieve refined management of river basins, a three-level zoning theory is proposed based on the structural characteristics of the ecosystem, building on primary and secondary zoning of the river basin. This theory aims to reflect the spatial differences in the functions of the river basin's ecosystem.

2.1. Zoning Methods

Utilizing a top–down approach, the first and second levels of ecosystem function zoning in watersheds are analyzed using cutting-edge remote sensing and Geographic Information System (GIS) technologies. Large-scale factor distribution maps are spatially overlapped to construct ecological zoning based on various types of aquatic ecosystems. The third-level zoning employs a bottom–up approach at a smaller scale, involving an in-depth analysis of major ecological environmental factors within the study area using GIS techniques and remote sensing. Weight coefficients for indicators are determined in collaboration with expert experience to calculate the zoning values for each level, with the sub-watershed serving as the fundamental unit for zoning. The specific process is detailed in Figure 1. Based on the spatial ecological pattern and evolution characteristics formed under the combined influence of natural geographical features and human activities in Shenzhen City, this paper proposes a three-level framework for ecological functional zoning, corresponding to the spatial scales of watershed, sub-watershed, and river. Different levels of zoning employ different indicators, with subordinate zones constrained by the scope of higher-level zones.

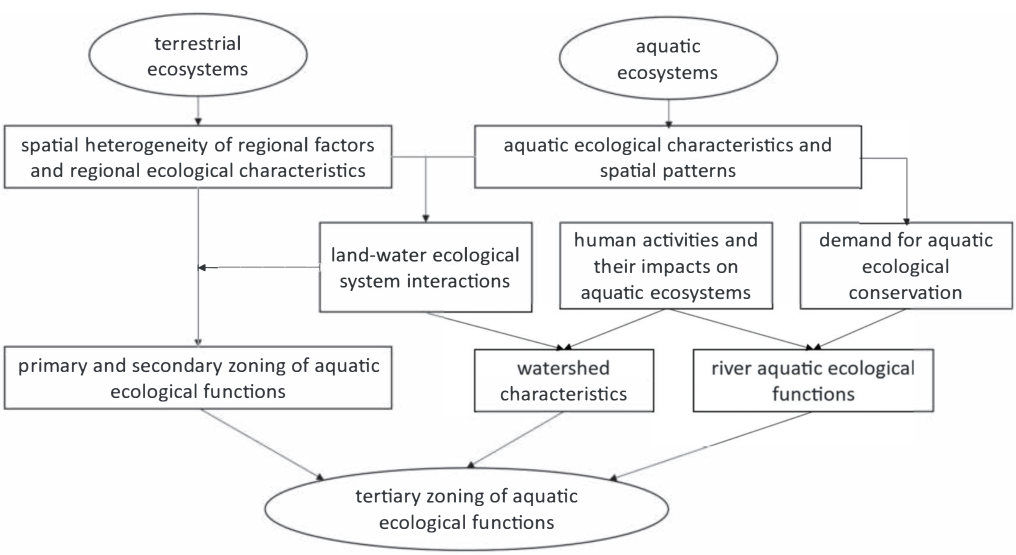

Figure 1. The process flowchart for watershed ecological functional zoning.

2.2. Sub-Watershed Unit Division Techniques

The determination of the study area's scope and boundary involves generating the watershed boundary through the application of a digital elevation model (DEM) and adjusting the sub-regions based on the water system map. The resolution of the DEM utilized for sub-watershed division is intricately determined based on data availability and the scale of the three-level zoning, typically employing a 90 m resolution elevation dataset.

2.3. Construction of Indicator System for Three-Level Zoning

The selection of indicators for three-level zoning primarily revolves around considering the influential factors of watershed characteristics on the structure of water ecosystems, aiming to differentiate the characteristics of diverse regional habitats and functional disparities. Not only do the natural conditions of rivers play a pivotal role, but the surrounding landscape and human activities are also significant factors impacting river ecosystems at the catchment scale. Therefore, the selection of candidate indicators for three-level zoning should encapsulate the influence of both natural and human activities on the structure of water ecosystems.

2.4. Techniques for Identification of Main Functions

Based on the established zoning and classification system for rivers in Shenzhen, Zhang et al. [36] focused on the ecological flow of the Shenzhen River. This research underscores the importance of tailored ecological flow assessments based on river characteristics and geographical zones, contributing to more effective and sustainable river management strategies.

The framework proposes a three-level hydro-ecological functional zoning system corresponding to three spatial scales: basin, sub-basin, and river. This aims to achieve finer-scale watershed management. Based on primary and secondary divisions within the watershed, the theory proposes a three-level zoning approach grounded in the structural characteristics of aquatic ecosystems. This framework aims to reflect spatial variations in the functional capabilities of watershed aquatic ecosystems.

The indicators for each level of zoning reflect specific features influenced by regional backgrounds at the ecosystem type level for the primary zone, and spatial differentiation rules for natural environmental factors such as topography, climate, and hydrology affecting regional ecosystem differences at the watershed scale. The indicators for the secondary zone reflect spatial differentiation rules for natural environmental factors such as topography and vegetation affecting regional ecosystem differences at the sub-watershed scale. The indicators for the tertiary zone characterize the river type and functional differences influenced by land use and river structures at the watershed scale. Tölgyesi et al. [37] used single statistical tests to compare vegetation units based on relative ecological indicator values with different approaches and weighting methods. The weights of the evaluation indicators are determined through an extensive literature review and expert judgment [38,39].

In summary, this study presents a robust framework for regional ecological functional zoning, incorporating state-of-the-art technologies, expert insights, and comprehensive indicator systems to effectively manage ecosystem functions within watersheds.

3. Case Study

3.1. Overview of the Study Area and Data

Shenzhen, a prominent city comprising nine administrative districts and one new district, occupies a land area of 1997.47 square kilometers. Situated in the south-central coastal region of Guangdong Province, China (as shown in Figure 2). Shenzhen's rapid development faces significant challenges due to its scarcity of resources and energy as one of China's initial cities committed to low-carbon development [40]. The city's economic, social, and ecological demands are substantial, necessitating an urgent exploration of pathways toward green, low-carbon, and efficient development. Shenzhen's urban development is intertwined with a complex ecological pattern shaped by both natural evolution and recent human interventions [41]. The integration of land and sea forms a sophisticated system, wherein the destruction of terrestrial and marine ecosystems, regional cross-media pollution, and interactions between natural and anthropogenic factors pose severe environmental stressors, hindering sustainable development. Long-standing segmented management of terrestrial and marine ecological environments exacerbates this challenge. The city's development is intricately linked to material and energy exchanges between its urban and marine components, reflecting a coupled and mutually influential integrated ecological system. Effective environmental strategies must therefore adopt a holistic approach, coordinating land–sea management to address ecological challenges and provide robust theoretical and technological support for Shenzhen's sustainable development as a special economic zone.

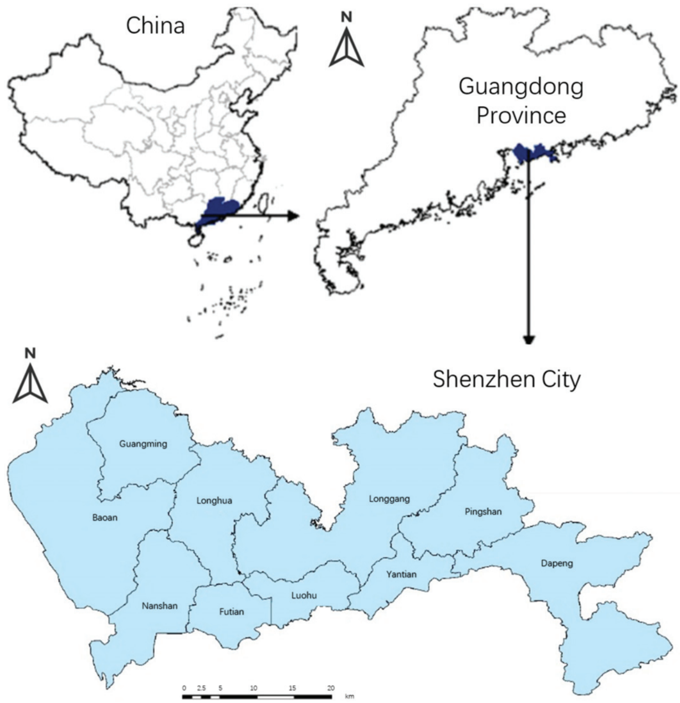

Figure 2. The boundary of Shenzhen City and its location in Guangdong Province, China.

The land use data for Shenzhen in 2020, including the classification data based on GlobelLand30, are sourced from various entities. Socio-economic data, such as population and GDP, are provided by the Resource and Environmental Science and Data Center. Climate and environmental data, including soil type, annual average temperature, and annual average precipitation, are also sourced from the Resource and Environmental Science and Data Center. Elevation and slope data come from the Geographic Spatial Data Cloud, while the distances to water bodies (rivers) and lakes are obtained from the National Geographic Information Resource Catalog Service System. All data are projected using the WGS_1984_UTM_Zone_51N coordinate system.

High-resolution geospatial data, including the 1:250,000 digital elevation model (DEM) and 1:250,000 water system map of the Shenzhen region, were utilized in this study, in conjunction with advanced geospatial analysis tools such as the Arc Hydro Tools module in ArcGIS 10.8. Predefined sub-division criteria for sub-regions were adhered to, leading to the successful delineation and extraction of small watershed units within the urban expanse of Shenzhen. A total of 148 defined sub-region units across the entirety of the study area were yielded by analysis, as illustrated in Figure 3.

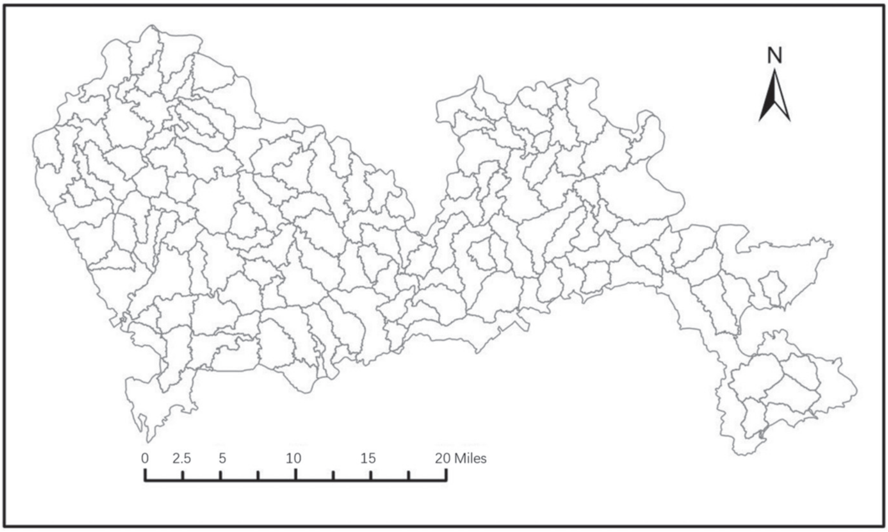

Figure 3. The sub-regional unit map of Shenzhen City.

This detailed geospatial analysis not only provides valuable insights into the unique topographical characteristics of Shenzhen, but also lays a solid foundation for further research in urban planning, environmental management, and sustainable development initiatives within the region.

3.2. Identification of Candidate Indicators

The establishment of a three-level ecological function sub-division index necessitates the incorporation of watershed characteristic indicators, along with the assessment of human activities' influence on aquatic ecosystems. Considering the distinctive features of the Shenzhen region and considering the ecological relevance, typology, and accessibility of sub-division indicators, a meticulous selection of candidate indicators and their corresponding ecological significance was undertaken and is comprehensively presented in Table 1.

Table 1. Statistical values of alternative indicators of zoning.

	Index	Unit	Minimum	Maximum	Range	Mean	Standard Deviation	Coefficient of Variation (%)
F1	Forest Area Ratio	%	0.00	100.00	100.00	36.00	34.50	95.92
F2	GDP Per Unit Area	10^4 CNY/km^2	0.00	29,550.30	29,550.30	362.67	1343.41	370.42
F3	Drainage Density	km^{-1}	0.00	6.60	6.60	0.46	0.44	96.64
F4	Farmland Area Ratio	%	0.00	100.00	100.00	37.00	31.50	85.13
F5	Urban Area Ratio	%	0.00	95.00	95.00	3.00	6.12	204.20
F6	Watershed Slope	Degree	0.00	17.56	17.56	4.00	3.61	90.14
F7	Watershed Slope Direction	-	0.00	286.24	286.24	170.43	21.31	12.50
F8	Water Area Ratio	%	0.00	100.00	100.00	3.00	8.90	296.67
F9	Volume of Water	mm	0.00	13,667.88	13,667.88	5419.74	1085.70	20.03
F10	Population Density	p/km^2	0.00	10,841.00	10,841.00	116.91	446.76	382.13
F11	Grassland Area Ratio	%	0.00	100.00	100.00	11.00	15.90	144.30

The indicators used in three-level zoning play a crucial role in assessing how watershed characteristics shape aquatic ecosystems, delineating diverse habitat features and functional distinctions among different geographical regions. These indicators encompass not only the inherent natural conditions of rivers, but also the broader landscape context [42]. Moreover, human activities, particularly alterations in local land use patterns, exert profound impacts on riverine ecology at the watershed scale. Thus, when selecting alternative indicators for tertiary zoning, it is essential to consider these anthropogenic influences alongside natural factors [43,44]. Methods employed for indicator selection include rigorous sensitivity analyses to gauge data variability, spatial autocorrelation analyses to understand the spatial patterns of the environmental factors, and statistical approaches such as the Principal Component Analysis and correlation analyses to identify key influencing factors.

The data sources and acquisition methods for these candidate indicators encompassed a range of thematic maps, such as digital elevation models, water system maps, administrative boundary maps, and land use maps specific to the Shenzhen region provided by the Resource and Environmental Science and Data Center, China. The spatial resolution of the geographic information is 90 m. Each thematic map was integral to the calculation of the sub-division index.

Drawing upon the 2020 vector data map of land use in Shenzhen offered by the Resource and Environmental Science and Data Center, China, this study focused on the extraction of six distinct land use categories, namely farmland, forest land, grassland, water area, urban area, and unused layers. An overlay analysis was conducted to derive dBase-type data for each layer within the small watershed unit, facilitating subsequent calculations of the proportion of land use types within each specific small watershed unit using the following Formula (1):

$$P_I(\%) = \frac{\sum A_i}{\sum A_T} \quad (1)$$

where P_I is the area proportion of each land type, A_i is the area of each land type in each small watershed unit, and A_T is the area of the delineated small watershed.

3.2.1. Sensitivity Analysis of Indicators

The usability of data in a sub-division analysis is contingent upon its sensitivity. Hence, the candidate indicators for the Shenzhen sub-division underwent an initial sensitivity analysis using SPSS 20.0 software to assess their suitability. The coefficient of variation for each indicator is detailed in Table 1. Notably, indicators such as population density, GDP per unit area, urban area ratio, and grassland area ratio exhibited coefficients of variation exceeding 100%, signifying substantial variability capable of capturing spatial environmental nuances and thus enhancing the efficacy of the sub-division analysis. Conversely, the watershed slope and water volume demonstrated coefficients of variation at 12.50% and 20.03%, respectively, indicating minimal variability and homogeneous characteristics across the watershed.

Consequently, guided by the sensitivity analysis outcomes, the watershed slope direction and water volume were excluded from further consideration. The ensuing selection of indicators for an in-depth analysis comprised population density, GDP per unit area, water area ratio, urban area ratio, grassland area ratio, drainage density, forest area ratio, watershed slope, and farmland area ratio.

3.2.2. Factor Analysis

In this study, a factor analysis was conducted to identify the primary factors that define the water environment in Shenzhen and to select indicators with the most significant contribution to the sub-division results. The varimax rotation method [45] was employed to ensure the independence of factors, and the determination of the number of common factors extracted was based on the criterion that the eigenvalue should surpass 1.0 [46]. Table 2 presents the characteristic values of the candidate indicators at various sub-division levels, indicating the extraction of four common factors.

Table 2. Eigenvalues of factor analysis of alternative indicators.

Principal Component	Initial Eigenvalue			Selection Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Sum	Variance %	Accumulate %	Sum	Variance %	Accumulate %	Sum	Variance %	Accumulate %
1	2.890	32.110	32.110	2.890	32.110	32.110	2.461	27.341	27.341
2	1.717	19.076	51.186	1.717	19.076	51.186	2.063	22.924	50.265
3	1.372	15.241	66.426	1.372	15.241	66.426	1.411	15.680	65.945
4	1.095	12.171	78.597	1.095	12.171	78.597	1.139	12.652	78.597

Refer to Table 3 for the composition matrix post-factor rotation utilizing the maximum variance orthogonal method. In the current study, factor loadings greater than 0.75 were deemed significant [47] and this classification was adopted by Singh et al. [48] and Qian et al. [49]. Indicators exhibiting factor loading values surpassing 0.75 were selected, encompassing forest area ratio, farmland area ratio, watershed slope, population density, urban area ratio, water area ratio, drainage density, and GDP per unit area, for further scrutiny.

Table 3. Alternative index factor analysis rotation component matrix.

	Principal Component 1	Principal Component 2	Principal Component 3	Principal Component 4
Zscore (F1)	0.932	−0.218	−0.118	−0.142
Zscore (F2)	−0.013	−0.086	−0.064	0.977
Zscore (F3)	−0.082	0.030	0.821	0.062
Zscore (F4)	0.854	0.061	−0.174	−0.361
Zscore (F5)	−0.222	0.841	−0.058	−0.091
Zscore (F6)	0.884	−0.107	−0.172	−0.097
Zscore (F8)	−0.031	0.047	0.765	−0.105
Zscore (F10)	−0.057	0.885	−0.062	−0.036
Zscore (F11)	−0.013	0.727	0.252	0.001

3.2.3. Aquatic Biological Correlations Analysis

The correlation between environmental indicators and aquatic biological attributes was examined to elucidate the principal environmental factors influencing the spatial distribution of aquatic ecosystems, and to ascertain the environmental indicators exhibiting strong correlations with the spatial distribution of aquatic organisms. Leveraging aquatic biological survey data spanning from 2015 to 2020 in the Shenzhen region, ArcGIS software was adeptly employed to extract the sub-division index data for each sampling point's small watershed, composing an environmental data matrix comprising candidate sub-division indicators.

Initially, a detrended correspondence analysis (DCA) [50] was conducted on the algae indicators, revealing an eigenvalue of 2.208 < 4, thereby indicating the appropriateness of a redundancy analysis (RDA) [51] for probing the relationship between the algae plant community and sub-division indicators. Through a Mantel Carlo test analysis in RDA, all sub-division indicators exhibited noteworthy correlations with the first sorting axis (AX1) (F = 30.321 and $p = 0.002$) and all sorting axes (F = 2.971 and $p = 0.004$).

The RDA analysis outcomes concerning the algae plant community and environmental factors are delineated in Table 4. Drawing insights from the factor analysis results, four common factors were discerned. The foremost eigenvalue surfaced on the first sorting axis (AX1), which emerges as the predominant factor dictating the distribution of algae plant communities. AX1 mirrors the extent of the environmental factors' impact on the distribution of algae plant communities, with a correlation coefficient of 0.720 between AX1 and the environmental factors, signifying a robust correlation. The Shenzhen sub-division candidate indicators and algae plant community RDA dual-axis plot are portrayed in Figure 4. The arrows symbolize the candidate sub-division indicators, with the length of the line segment denoting the degree of correlation between the indicator and the biological community, the angle between the arrow connection and the sorting axis representing the level of correlation with the water environment, and the quadrant in which the arrow is positioned indicating a positive or negative correlation with the water environment.

Table 4. RDA analysis results of algae community and environmental factors.

Axis	Eigenvalue	Correlation Coefficient	Cumulative Percentage of Variance	
			Species	Species-Environment
AX1	0.464	0.720	46.438	96.109
AX2	0.008	0.483	47.323	97.920
AX3	0.006	0.547	47.935	99.243
AX4	0.004	0.292	48.321	100.000

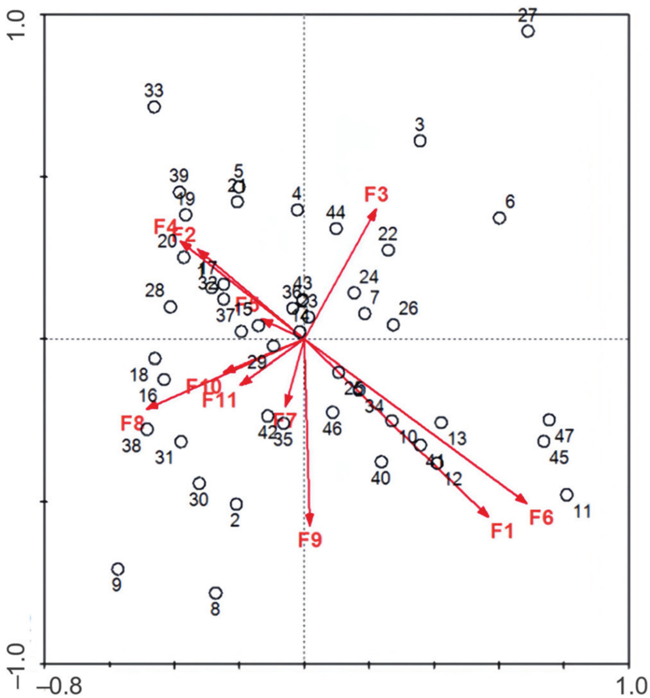

Figure 4. Alternative indicators of tertiary zoning and RDA analysis results of algae community.

Based on the findings presented in Figure 4, it is evident that watershed slope (F6) exhibited a positive correlation with AX1, demonstrating the highest correlation coefficient of 0.495. Similarly, forest area ratio (F1) demonstrated a positive correlation with AX1, boasting a correlation coefficient of 0.4098. In contrast, water area ratio (F8), farmland area ratio (F4), and GDP per unit area (F2) were found to be negatively correlated with AX1, with corresponding correlation coefficients of −0.350, −0.276, and −0.236, respectively. Although population density (F10), urban area ratio (F5), and drainage density (F3) did not exhibit significant correlations with AX1, the retention of the urban area ratio was deemed essential to signify the impact of human activities on aquatic ecosystems.

3.2.4. Correlation Analysis

To assess the independence of information among the selected parameters, a correlation analysis was conducted on the ecological correlation-selected indicators, employing the correlation coefficient to quantify the relative strength of the relationship between the quantitative variables. When the absolute value of the correlation coefficient $|R| < 0.5$, it suggests a substantial degree of information overlap between the two indicators, thereby necessitating the removal of environmental factors with diminished information content to uphold the independence of the sub-division indicators [52].

The outcomes of the indicator correlation analysis are detailed in Table 5. Notably, the correlation coefficients between forest area ratio and watershed slope, as well as farmland area ratio, were determined to be 0.422 and 0.444, respectively. Furthermore, the correlation coefficient between watershed slope and farmland area ratio stood at 0.399, bearing a significant level of 0.000, signifying a substantial correlation. Additionally, the correlation coefficient between urban area ratio and watershed slope was determined to be −0.254, also demonstrating a significant correlation. Despite the significant correlation trends observed in the candidate indicators for the three-level sub-division, their correlation coefficients all fell below 0.5, indicating a limited degree of information overlap between the candidate indicators, thereby warranting their retention.

Table 5. Correlation analysis matrix of three-level alternative indicators.

		F1	**F2**	**F4**	**F5**	**F6**	**F8**
F1	Pearson correlation	1					
	Significance (bilateral)						
F2	Pearson correlation	−0.129 **	1				
	Significance (bilateral)	0.000					
F4	Pearson correlation	−0.444 **	−0.290 **	1			
	Significance (bilateral)	0.000	0.000				
F5	Pearson correlation	−0.303 **	−0.143 **	0.242 **	1		
	Significance (bilateral)	0.000	0.000	0.000			
F6	Pearson correlation	0.422 **	−0.043 **	−0.399 **	−0.254 **	1	
	Significance (bilateral)	0.000	0.000	0.000	0.000		
F8	Pearson correlation	−0.117 **	−0.078 **	−0.050 **	0.068 **	−0.141 **	1
	Significance (bilateral)	0.000	0.000	0.000	0.000	0.000	

** Significant correlation at 0.01 level (bilateral).

In summary, following a correlation analysis, six indicators—forest area ratio, urban area ratio, GDP per unit area, water area ratio, watershed slope, and farmland area ratio—were identified as the three-level sub-division indicators for ecological function in Shenzhen.

3.3. Shenzhen City Ecological Function Three-Level Zoning

3.3.1. Zoning Index Spatialization

The spatialization of various indicators was conducted to illustrate the spatial distribution and variation of Shenzhen City's ecological function three-level zoning indicators, as depicted in Figure 5. Variations in the six zoning indicators were observed.

The forest area ratio in Shenzhen City ranges from 0 to 100%, with a total forest area of approximately 64,323.61 hectares and an average forest area ratio of 32%. This encompasses various types of forest land such as tree forests, bamboo forests, shrub lands, and other forest lands. The distribution shows larger forest areas in high-altitude mountainous regions and smaller forest areas in low-altitude plain areas. Specifically, tree forests cover 62,682.69 hectares, accounting for 97%; bamboo forests cover 42.86 hectares, accounting for 0.07%; shrub lands cover 747.21 hectares, accounting for 1.16%; and other forest lands cover 850.85 hectares, accounting for 1%. Forest lands are predominantly concentrated in the Dapeng, Longgang, and Pingshan districts, constituting 63% of the city's forest land.

The agricultural land area ratio in Shenzhen City ranges from 0 to 50%, with a cultivated land area of approximately 2844.74 hectares and an average agricultural land area ratio of 2%. This includes paddy fields, irrigated lands, and dry lands. Cultivated lands are mainly clustered in the Guangming, Bao'an, and Pingshan districts, representing 66% of the city's cultivated land.

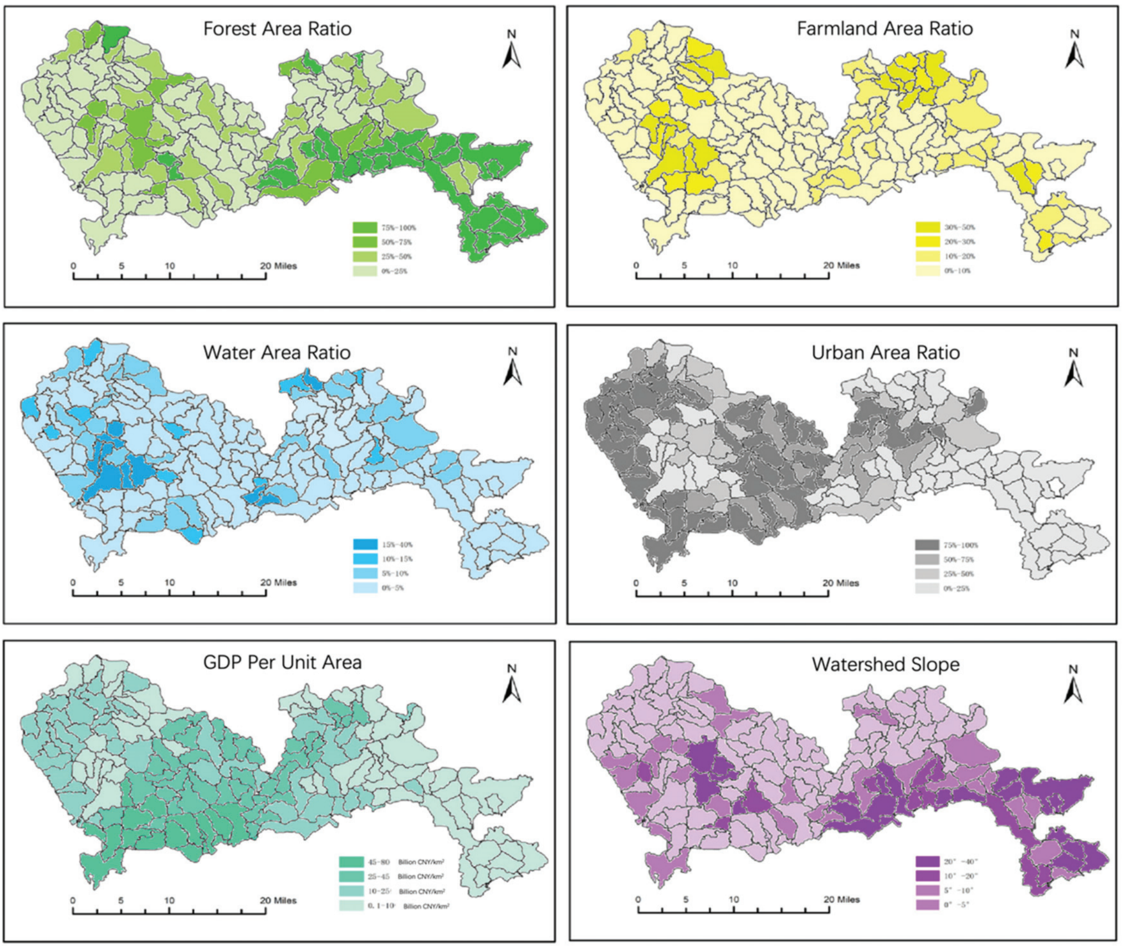

Figure 5. Map of Shenzhen City's ecological function three-level zoning indicators.

The water area ratio in Shenzhen City ranges from 0 to 35%, with water bodies and water facilities covering approximately 9392.55 hectares and an average water area ratio of 5%. This includes river water surfaces, lake water surfaces, reservoir water surfaces, pond water surfaces, channels, and water engineering construction lands. Water bodies and water facilities are prominently present in the Bao'an, Longgang, and Dapeng districts, comprising 58% of the city's water area.

The urban area ratio in Shenzhen City spans from 0 to 100%, with urban, rural village, and industrial lands covering approximately 92,416.05 hectares, with an average of 46%. This category includes various types of urban lands, rural residential areas, mining and industrial construction areas, scenic spots, and special land uses.

The GDP per unit area in Shenzhen City ranges from 0.1 to 7.2 $\times$ 10^5 CNY/km^2, with an average value of 1.62 $\times$ 10^5 CNY/km^2. The distribution closely aligns with the urban area ratio distribution in Shenzhen City.

The regional slope in Shenzhen City ranges from 0 to 39.56 degrees, with an average of 5 degrees. Steeper slopes are predominantly found in Dapeng New District, Yantian District, and the junction of the Nanshan and Bao'an Nanshan districts.

3.3.2. Indicator Weight

This study employs the entropy weight method [53] to determine the weight of each indicator. This method objectively evaluates the importance of indicator factors based on the information provided by the observation values of each indicator. The calculation steps are detailed as follows [53]:

Construct an $i \times j$ matrix with the indicator data as column vectors.

Calculate the characteristic weight (P_{ij}) of the j-th indicator for the i-th measurement value using Formula (2).

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{2}$$

Compute the entropy of each indicator (e_j) based on the characteristic weight using Formula (3).

$$e_j = -\frac{1}{ln\ n}\sum_{i=1}^{n} P_{ij} ln\ P_{ij} \tag{3}$$

Determine the weight of each indicator (w_j) according to Formula (4).

$$w_j = (1 - e_{ij})/\sum_{j=1}^{n}(1 - e_{ij}) \tag{4}$$

The results of the ecological indicators' weights in Shenzhen City are presented in Table 6.

Table 6. Weight of zoning indicators.

Index	Weight
Forest area ratio	0.170
farmland area ratio	0.140
Water area ratio	0.246
Urban area ratio	0.256
GDP per unit area	0.068
Watershed slope	0.120

3.3.3. Comprehensive Indicators Analysis

Following the determination of the weight factors for each indicator, a weighted sum calculation is applied to each zoning indicator within the range of each zoning unit. This process yields the comprehensive value for each small watershed in Shenzhen City. The spatial distribution map illustrating Shenzhen City's ecological function comprehensive values is depicted in Figure 6.

In this study, the K-means algorithm is employed to conduct a spatial clustering analysis within each secondary zone based on the comprehensive value of water ecological function. Subsequently, zoning boundaries are established through expert analysis and adherence to the principle of sub-zone integrity, leading to the delineation of tertiary zoning results.

Shenzhen City is partitioned into 24 ecological function three-level areas as shown in Figure 7. These divisions exhibit significant variations in ecosystem characteristics and background conditions, primarily manifesting through distinctive zoning indicators. The differentiation in ecological function zoning across Shenzhen underscores the diverse ecological landscapes and environmental attributes present within the region.

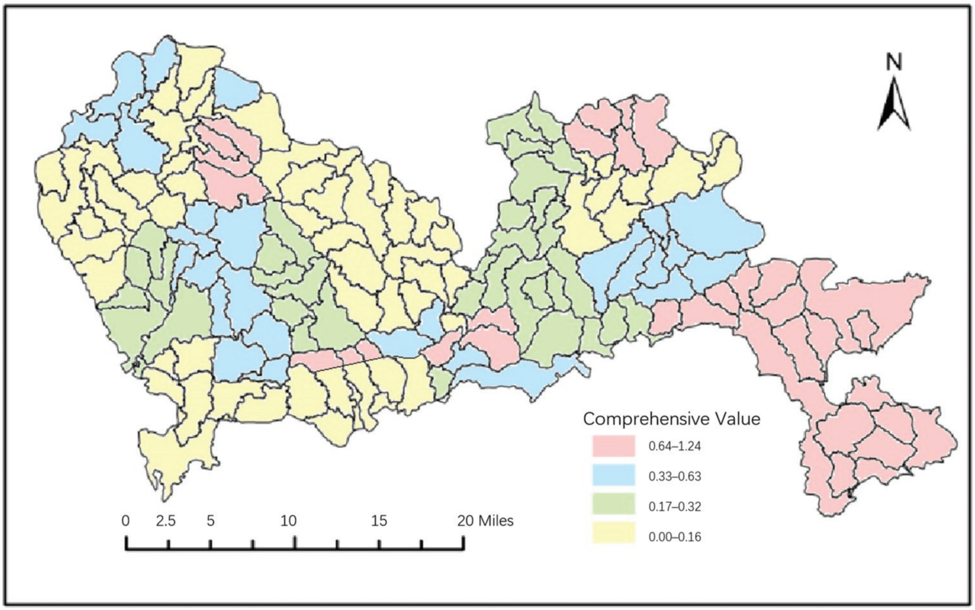

Figure 6. Comprehensive value of ecological function in Shenzhen.

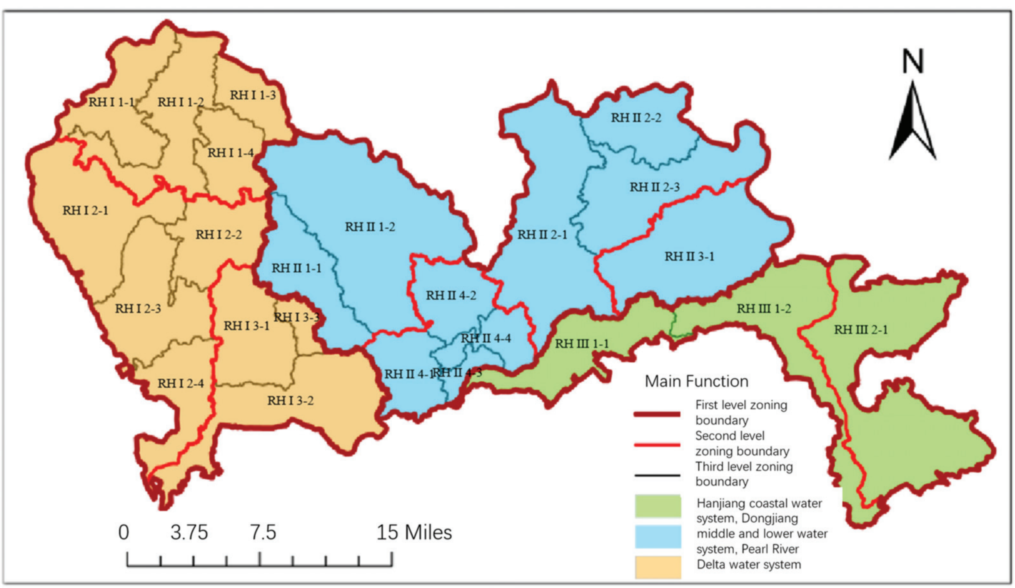

Figure 7. The three-level zoning map of Shenzhen City.

In terms of spatial distribution, the primary functional differences among the three ecological functional zones in Shenzhen are significant. The upper reaches of the watershed are mostly characterized by ecological maintenance and water conservation functions, with Dapeng New District predominantly being an ecological maintenance area. The urban support areas are mainly concentrated in the upper reaches of the watershed, such as Futian District, Luohu District, and Nanshan District. The agricultural production areas are mainly located in the flat areas with sufficient water sources and lower slopes, primarily in the northeast corner of Longgang District and Nanshan District.

According to the three-level zoning, policymakers can develop plans more specifically. For example, RHI1-1 focuses on the upstream basin of the Maozhou River in the Pearl River Delta, emphasizing the conservation of high-functioning habitats, including protecting forest ecosystems and biodiversity by strictly prohibiting deforestation for cultivation, enhancing river protection awareness, implementing reasonable conservation measures, establishing a strict development approval system, and preventing soil erosion. RHI2-3 focuses on the hilly river types within the midstream basin of the Pearl River Delta's Zhujiang Estuary, emphasizing high-function water source protection areas. It aims to improve water body environments by avoiding human activities that disturb them, minimizing large-scale hydraulic construction, enhancing river protection awareness, implementing reasonable conservation measures, establishing a strict development approval system, preventing soil erosion, and suggesting water quality management goals in line with Class III water quality standards. RHII1-2 focuses on the urban support function area of the urban river types in the Guanlan River basin of the Dongjiang River system, emphasizing high-pressure functional restoration. It involves restructuring industries to include investments in high-tech and non-polluting projects, improving regional environments, and promoting ecological urban development. This includes implementing reasonable conservation measures and establishing a strict development approval system.

4. Discussion

Several studies indicate that changes in urban coastal ecosystems are closely related to land–sea utilization, coverage types, terrestrial inputs, management, and development practices. Terrestrial ecosystems significantly impact nearshore ecological systems and their evolution. The substantial material and energy flows driven by human activities on land contribute to uncertainties in the evolution of coastal ecosystems, leading to environmental degradation. Hong et al. [54] indicated consistent ecological corridor sensitivity grades in Shenzhen, with high sensitivity in the north and low values in the south, dominated by moderately sensitive corridors. A land-use control program is designed considering current management practices and future land demands, outlining withdrawal, reservation, occupation, and avoidance policies. Peng et al. [55] explored the dynamics of urban ecological land in Shenzhen City, driven by rapid urbanization and its associated socio-economic development and ecological protection conflicts. Using multivariate logistic regression, the research quantified the factors influencing these changes and maps the transition probabilities of ecological land. Factors such as slope, proximity to construction land, and the rate of growth in construction land were identified as crucial determinants influencing changes in urban ecological land.

The three-level ecological functional zoning framework developed in this study provides a robust foundation for policymakers, urban planners, and environmental managers to make informed decisions regarding land use, conservation efforts, and sustainable development in the Shenzhen region. By identifying and categorizing different ecological functions based on a comprehensive set of indicators and spatial analysis techniques, this zoning approach offers a nuanced understanding of the region's environmental characteristics and highlights areas of ecological significance that warrant special attention and protection.

Yi et al. [56] utilized a comparative evaluation approach to analyze changes in positive and negative ecological elements within Shenzhen's coastal zone. These elements were classified based on land uses derived from multiple remote sensing sources and a land-use degree index. The findings indicate that human activities have exerted stronger impacts on the west coast compared to the east coast of Shenzhen. It observed a gradual increase in environmental protection awareness of the government since 2000; however, this did not correspond to an improvement in ecosystem health. The research findings of this paper are consistent with that. Additionally, there has been a significant increase in research on ecosystem multifunctionality, which refers to the capacity of ecosystems to provide multiple functions and/or services simultaneously throughout the world [57]. This study enhances ecological planning and environmental management by offering a systematic, data-driven method for defining ecological functional zones in urbanizing areas. Compared to previous studies [58,59], the three-level zoning proposed in this paper provides more refined management of the study area, extending to the scales of watershed, sub-watershed, and river. Furthermore, this paper supports the conclusion that urban land use is crucial for zoning plans to foster sustainable urban development [27].

Furthermore, the application of the K-means algorithm for a spatial clustering analysis proved to be an effective method for delineating distinct ecological zones within the study area. This approach not only allows for the identification of areas with similar ecological functions, but also helps in recognizing spatial patterns and relationships among different environmental variables. Such insights are crucial for prioritizing conservation efforts, implementing targeted land management strategies, and promoting sustainable development practices that are in harmony with the natural environment.

Ecological zoning holds significant value for other regions worldwide. It provides insights into effective urban environmental management practices, sustainable development strategies, and approaches to balancing economic growth with ecological preservation. Shenzhen's experience can offer valuable lessons on integrating green spaces, conserving natural habitats, managing urban expansion, and promoting environmental sustainability amidst rapid urbanization. These lessons can be adapted and applied in various global contexts facing similar challenges of urban development and environmental conservation [60,61].

It is important to note that the results of this study are contingent upon the availability and accuracy of the input data, as well as the assumptions and criteria used in the ecological zoning process. Future research could benefit from incorporating more detailed field surveys, remote sensing data, and stakeholder consultations to validate and refine the zoning framework presented here. Additionally, the continuous monitoring and evaluation of the ecological conditions in the Shenzhen region will be essential to assess the effectiveness of the zoning scheme over time, and to adapt it to changing environmental dynamics and human activities. The shortcomings of ecological zoning methods include complexity in integrating diverse marine and terrestrial ecosystem data and difficulty in addressing spatial and temporal dynamics of both marine and terrestrial environments simultaneously [62–64]. There is a limited availability of comprehensive datasets covering both marine and terrestrial ecosystems. Future research will also include exploring how ecological zoning impacts carbon emission markets, since ecological zoning and carbon emission markets are interconnected in several ways.

Overall, this research contributes to the broader discourse on ecological planning and environmental management by offering a systematic and data-driven approach to delineating ecological functional zones in urbanizing regions. By integrating spatial analysis techniques, ecological indicators, and stakeholder engagement, this study lays the groundwork for promoting sustainable development practices that safeguard ecological integrity and enhance the quality of life for current and future generations in Shenzhen.

5. Conclusions

Rapid global economic development has brought significant challenges in the form of overexploitation and the depletion of ecological resources, as well as environmental degradation. As a result, research focus has shifted towards watershed-based ecological management, with a particular emphasis on ecological zoning. To address the evolving needs of ecological environment management and protection, ecological zoning has become a primary approach for regional ecological environment management in the future.

This paper establishes a three-level zoning theoretical framework for river basin aquatic ecology and conducts a practical case study in Shenzhen, a representative coastal city. This study includes the completion of a three-level zoning of terrestrial and shoreline aquatic ecological functions in Shenzhen, as well as an assessment of shoreline development suitability, leading to the following key conclusions:

1. Definition and framework of watershed ecological function zoning: The concept and system of ecological zoning are elucidated. This method not only reflects the impact of natural factors on ecological systems, but also quantitatively incorporates the influence of human activities within a certain range. It considers the dual function of aquatic ecosystems in self-sustaining and providing water resources for human needs. Considering the spatial scales of different watershed levels, the hierarchical structural characteristics of aquatic ecosystems, and other factors, a comprehensive framework for the three-level zoning of watershed aquatic ecological functions is proposed. Specific zoning methods for different levels within the system are suggested, ultimately establishing a complete technical roadmap and research methodology for the three-level zoning of watershed aquatic ecology.
2. Theoretical basis and technical methods for three-level zoning of river basin aquatic ecological functions: Based on the integrity of aquatic ecosystems, a structural characteristic index is proposed as the three-level zoning indicator for watershed aquatic ecological functions. This index can distinguish habitat characteristics and functional differences in different regions, thus enabling more effective management. In pursuit of finer river basin management, a three-level zoning theory based on the structural characteristics of aquatic ecosystems is presented, complementing the existing two-level zoning. This expanded framework better captures the spatial variability of aquatic ecosystem functions within river basins. Additionally, corresponding zoning objectives and unique principles are introduced. Guided by the three-level zoning theory, this paper proposes a method for dividing zoning units (sub-basin units), covering the division, indicator system construction, zoning technology, technical pathways, and main function identification.
3. Completion of three-level zoning for terrestrial aquatic ecological functions in Shenzhen: In line with ecological zoning goals, 148 small basin units were identified. Through factor and correlation analyses, six key three-level zoning indicators for aquatic ecosystems were established, with weights determined by the entropy weight method. A spatial cluster analysis was used to integrate these results, resulting in 24 zones with distinct aquatic ecological functions. Standards for ecological function assessment, indicator weights, and evaluation principles were defined, with zoning results validated through a spatial functional analysis, finalizing the three-level zoning plan for Shenzhen.

Through this comprehensive investigation, this study not only contributes to the theoretical understanding of watershed aquatic ecological function zoning, but also provides valuable insights and a solid methodology for its practical implementation, as demonstrated in the detailed case study in Shenzhen.

Author Contributions: Conceptualization, Y.L. and H.Y. (Han Yu); methodology, H.Y. (Han Yu); software, F.Z.; validation, F.Z. and R.L.; investigation, F.Z. and R.L.; resources, H.Y. (Hongbing Yu); writing—original draft preparation, Y.L.; writing—review and editing, H.Y. (Han Yu); supervision, Y.C.; funding acquisition, H.Y. (Han Yu). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Shenzhen Science and Technology Program, grant number No. KCXFZ20211020172542001.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to the data management regulations of the Shenzhen Research Institute of Nankai University.

Conflicts of Interest: Author Yao Chen was employed by the company Shenzhen Lightsun Analysis and Testing Center Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Fang, Q.; Zhang, L.; Hong, H.; Zhang, L.; Bristow, F. Ecological function zoning for environmental planning at different levels. *Environ. Dev. Sustain.* **2008**, *10*, 41–49. [CrossRef]
2. Xu, F.; Shao, Y.; Xu, B.; Li, H.; Xie, X.; Xu, Y.; Pu, L. Evaluation and zoning of cultivated land quality based on a space–function–environment. *Land* **2023**, *12*, 174. [CrossRef]
3. Talukdar, G.; Bhattacharjya, R.K.; Sarma, A.K. Understanding the effect of long term and short term hydrological components on landscape ecosystem. *Ecol. Inform.* **2023**, *77*, 102267. [CrossRef]
4. Deng, Y.; Ming, L.; Hai, Y.; Chen, H.; Jize, D.; Luo, J.; Yan, X.; Zhang, X.; Yao, S.; Hou, M. Has the Establishment of National Key Ecological Function Zones Improved Eco-Environmental Quality?—Evidence from a Quasi-Natural Experiment in 130 Counties in Sichuan Province, China. *Land* **2024**, *13*, 677. [CrossRef]
5. Merriam, C.H. *Life Zones and Crop Zones of the United States (No. 10)*; US Government Printing Office: Washington, DC, USA, 1898; pp. 7–8.
6. Dong, J.; Metternicht, G.; Hostert, P.; Fensholt, R.; Chowdhury, R.R. Remote sensing and geospatial technologies in support of a normative land system science: Status and prospects. *Curr. Opin. Environ. Sustain.* **2019**, *38*, 44–52. [CrossRef]
7. Liu, C.; Li, W.; Zhu, G.; Zhou, H.; Yan, H.; Xue, P. Land use/land cover changes and their driving factors in the Northeastern Tibetan Plateau based on Geographical Detectors and Google Earth Engine: A case study in Gannan Prefecture. *Remote Sens.* **2020**, *12*, 3139. [CrossRef]
8. Aryal, B.; Escarzaga, S.M.; Vargas Zesati, S.A.; Velez-Reyes, M.; Fuentes, O.; Tweedie, C. Semi-automated semantic segmentation of arctic shorelines using very high-resolution airborne imagery, spectral indices and weakly supervised machine learning approaches. *Remote Sens.* **2021**, *13*, 4572. [CrossRef]
9. Abdi, A.M. Land cover and land use classification performance of machine learning algorithms in a boreal landscape using Sentinel-2 data. *GIScience Remote Sens.* **2020**, *57*, 1–20. [CrossRef]
10. Martínez Prentice, R.; Villoslada Peciña, M.; Ward, R.D.; Bergamo, T.F.; Joyce, C.B.; Sepp, K. Machine learning classification and accuracy assessment from high-resolution images of coastal wetlands. *Remote Sens.* **2021**, *13*, 3669. [CrossRef]
11. Herridge, D.F.; Win, M.M.; Nwe, K.M.M.; Kyu, K.L.; Win, S.S.; Shwe, T.; Min, Y.Y.; Denton, M.D.; Cornish, P.S. The cropping systems of the Central Dry Zone of Myanmar: Productivity constraints and possible solutions. *Agric. Syst.* **2019**, *169*, 31–40. [CrossRef]
12. Wickware, G.M. Classification for Stratification, Mapping, and Data Display for Range Inventories: Comment and Discussion. In *Developing Strategies For Rangeland Management*; CRC Press: Boca Raton, FL, USA, 2021; pp. 631–646.
13. Dufour, S.; Rodríguez-González, P.M.; Laslier, M. Tracing the scientific trajectory of riparian vegetation studies: Main topics, approaches and needs in a globally changing world. *Sci. Total Environ.* **2019**, *653*, 1168–1185. [CrossRef] [PubMed]
14. Zheng, Z.; Wu, Z.; Chen, Y.; Yang, Z.; Marinello, F. Exploration of eco-environment and urbanization changes in coastal zones: A case study in China over the past 20 years. *Ecol. Indic.* **2020**, *119*, 106847. [CrossRef]
15. Li, Z.T.; Li, M.; Xia, B.C. Spatio-temporal dynamics of ecological security pattern of the Pearl River Delta urban agglomeration based on LUCC simulation. *Ecol. Indic.* **2020**, *114*, 106319. [CrossRef]
16. Gao, J.; Zou, C.; Zhang, K.; Xu, M.; Wang, Y. The establishment of Chinese ecological conservation redline and insights into improving international protected areas. *J. Environ. Manag.* **2020**, *264*, 110505. [CrossRef]
17. Li, X.; Yu, X.; Wu, K.; Feng, Z.; Liu, Y.; Li, X. Land-use zoning management to protecting the Regional Key Ecosystem Services: A case study in the city belt along the Chaobai River, China. *Sci. Total Environ.* **2021**, *762*, 143167. [CrossRef]
18. Zong, S.; Hu, Y.; Zhang, Y.; Wang, W. Identification of land use conflicts in China's coastal zones: From the perspective of ecological security. *Ocean Coast. Manag.* **2021**, *213*, 105841. [CrossRef]
19. Jin, X.; Wei, L.; Wang, Y.; Lu, Y. Construction of ecological security pattern based on the importance of ecosystem service functions and ecological sensitivity assessment: A case study in Fengxian County of Jiangsu Province, China. *Environ. Dev. Sustain.* **2021**, *23*, 563–590. [CrossRef]
20. Li, R.; Zheng, H.; Polasky, S.; Hawthorne, P.L.; O'Connor, P.; Wang, L.; Li, R.; Xiao, Y.; Wu, T.; Ouyang, Z. Ecosystem restoration on Hainan Island: Can we optimize for enhancing regulating services and poverty alleviation? *Environ. Res. Lett.* **2020**, *15*, 084039. [CrossRef]
21. Yang, L.; Li, X.; Yang, Q.; Zhang, L.; Zhang, S.; Wu, S.; Zhou, C. Extracting knowledge from legacy maps to delineate eco-geographical regions. *Int. J. Geogr. Inf. Sci.* **2021**, *35*, 250–272. [CrossRef]
22. Fu, B. Several key points in territorial ecological restoration. *Bull. Chin. Acad. Sci.* **2021**, *36*, 64–69.
23. Hong, W.; Jiang, R.; Yang, C.; Zhang, F.; Su, M.; Liao, Q. Establishing an ecological vulnerability assessment indicator system for spatial recognition and management of ecologically vulnerable areas in highly urbanized regions: A case study of Shenzhen, China. *Ecol. Indic.* **2016**, *69*, 540–547. [CrossRef]
24. Liu, J.; Jiang, T.; Ye, Z. Information efficiency research of China's carbon markets. *Financ. Res. Lett.* **2021**, *38*, 101444. [CrossRef]
25. Yu, X.; Wan, K.; Du, Q. Can carbon market policies achieve a "point-to-surface" effect?—Quasi-experimental evidence from China. *Energy Policy* **2023**, *183*, 113803. [CrossRef]

26. Lin, J.; Li, X. Large-scale ecological red line planning in urban agglomerations using a semi-automatic intelligent zoning method. *Sustain. Cities Soc.* **2019**, *46*, 101410. [CrossRef]
27. Domingo, D.; Palka, G.; Hersperger, A.M. Effect of zoning plans on urban land-use change: A multi-scenario simulation for supporting sustainable urban growth. *Sustain. Cities Soc.* **2021**, *69*, 102833. [CrossRef]
28. Xu, Z.; Peng, J.; Dong, J.; Liu, Y.; Liu, Q.; Lyu, D.; Qiao, R.; Zhang, Z. Spatial correlation between the changes of ecosystem service supply and demand: An ecological zoning approach. *Landsc. Urban Plan.* **2022**, *217*, 104258. [CrossRef]
29. Zhou, Y.; Wu, T.; Wang, Y. Urban expansion simulation and development-oriented zoning of rapidly urbanising areas: A case study of Hangzhou. *Sci. Total Environ.* **2022**, *807*, 150813. [CrossRef]
30. Liu, X.; Heilig, G.K.; Chen, J.; Heino, M. Interactions between economic growth and environmental quality in Shenzhen, China's first special economic zone. *Ecol. Econ.* **2007**, *62*, 559–570. [CrossRef]
31. Liu, X.; Su, Y.; Li, Z.; Zhang, S. Constructing ecological security patterns based on ecosystem services trade-offs and ecological sensitivity: A case study of Shenzhen metropolitan area, China. *Ecol. Indic.* **2023**, *154*, 110626. [CrossRef]
32. Wang, G.; Yang, D.; Xia, F.; Zhong, R.; Xiong, C. Three types of spatial function zoning in key ecological function areas based on ecological and economic coordinated development: A case study of Tacheng Basin, China. *Chin. Geogr. Sci.* **2019**, *29*, 689–699. [CrossRef]
33. Sun, M.; Yang, R.; Li, X.; Zhang, L.; Liu, Q. Designing a path for the sustainable development of key ecological function zones: A case study of southwest China. *Glob. Ecol. Conserv.* **2021**, *31*, e01840. [CrossRef]
34. Ning, J.; Liu, J.; Kuang, W.; Xu, X.; Zhang, S.; Yan, C.; Li, R.; Wu, S.; Hu, Y.; Du, G.; et al. Spatiotemporal patterns and characteristics of land-use change in China during 2010–2015. *J. Geogr. Sci.* **2018**, *28*, 547–562. [CrossRef]
35. Wang, W.; Jiao, L.; Jia, Q.; Liu, J.; Mao, W.; Xu, Z.; Li, W. Land use optimization modelling with ecological priority perspective for large-scale spatial planning. *Sustain. Cities Soc.* **2021**, *65*, 102575. [CrossRef]
36. Zhang, L.; Liu, J.; Wan, D.; Yao, H.; Zheng, J.; Jiang, Y. Analysis and calculation of ecological flow in Shenzhen River based on zoning and classification. In *Advances in Civil Engineering and Environmental Engineering*; CRC Press: Boca Raton, FL, USA, 2023; Volume 2, pp. 494–503.
37. Tölgyesi, C.; Bátori, Z.; Erdős, L. Using statistical tests on relative ecological indicator values to compare vegetation units–Different approaches and weighting methods. *Ecol. Indic.* **2014**, *36*, 441–446. [CrossRef]
38. Chi, G.; Yu, S.; Zhou, Y. A novel credit evaluation model based on the maximum discrimination of evaluation results. *Emerg. Mark. Financ. Trade* **2020**, *56*, 2543–2562. [CrossRef]
39. Li, Y.; Wang, X.K.; Zhang, H.Y.; Wang, J.Q.; Li, L. An integrated regional water quality assessment method considering interrelationships among monitoring indicators. *Environ. Monit. Assess.* **2021**, *193*, 1–20. [CrossRef]
40. Xian, C.; Gong, C.; Lu, F.; Wu, H.; Ouyang, Z. The evaluation of greenhouse gas emissions from sewage treatment with urbanization: Understanding the opportunities and challenges for climate change mitigation in China's low-carbon pilot city, Shenzhen. *Sci. Total Environ.* **2023**, *855*, 158629. [CrossRef] [PubMed]
41. Bin, Y.; Jingjing, J.; Lixin, M.; Peng, Y. Sustainable energy options for a low carbon demonstration city project in Shenzhen, China. *J. Renew. Sustain. Energy* **2015**, *7*, 023122. [CrossRef]
42. Czúcz, B.; Keith, H.; Maes, J.; Driver, A.; Jackson, B.; Nicholson, E.; Kiss, M.; Obst, C. Selection criteria for ecosystem condition indicators. *Ecol. Indic.* **2021**, *133*, 108376. [CrossRef]
43. Talke, S.A.; Jay, D.A. Changing tides: The role of natural and anthropogenic factors. *Annu. Rev. Mar. Sci.* **2020**, *12*, 121–151. [CrossRef]
44. Akhtar, N.; Syakir Ishak, M.I.; Bhawani, S.A.; Umar, K. Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water* **2021**, *13*, 2660. [CrossRef]
45. Kaiser, H.F. The varimax criterion for analytic rotation in factor analysis. *Psychometrika* **1958**, *23*, 187–200. [CrossRef]
46. Braeken, J.; Van Assen, M.A. An empirical Kaiser criterion. *Psychol. Methods* **2017**, *22*, 450. [CrossRef]
47. Liu, C.W.; Lin, K.H.; Kuo, Y.M. Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. *Sci. Total Environ.* **2003**, *313*, 77–89. [CrossRef]
48. Singh, K.P.; Malik, A.; Singh, V.K.; Mohan, D.; Sinha, S. Chemometric analysis of groundwater quality data of alluvial aquifer of Gangetic plain, North India. *Anal. Chim. Acta* **2005**, *550*, 82–91. [CrossRef]
49. Qian, Y.; Migliaccio, K.W.; Wan, Y.; Li, Y. Surface water quality evaluation using multivariate methods and a new water quality index in the Indian River Lagoon, Florida. *Water Resour. Res.* **2007**, *43*, 7–8. [CrossRef]
50. Hill, M.O.; Gauch, H.G., Jr. Detrended correspondence analysis: An improved ordination technique. *Vegetatio* **1980**, *42*, 47–58. [CrossRef]
51. Ter Braak, C.J.; Prentice, I.C. A theory of gradient analysis. In *Advances in Ecological Research*; Academic Press: Cambridge, MA, USA, 1988; Volume 18, pp. 271–317.
52. Asuero, A.G.; Sayago, A.; González, A.G. The correlation coefficient: An overview. *Crit. Rev. Anal. Chem.* **2006**, *36*, 41–59. [CrossRef]
53. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444. [CrossRef]
54. Hong, W.; Guo, R.; Su, M.; Tang, H.; Chen, L.; Hu, W. Sensitivity evaluation and land-use control of urban ecological corridors: A case study of Shenzhen, China. *Land Use Policy* **2017**, *62*, 316–325. [CrossRef]

55. Peng, J.; Zhao, M.; Guo, X.; Pan, Y.; Liu, Y. Spatial-temporal dynamics and associated driving forces of urban ecological land: A case study in Shenzhen City, China. *Habitat Int.* **2017**, *60*, 81–90. [CrossRef]
56. Yi, L.; Chen, J.; Jin, Z.; Quan, Y.; Han, P.; Guan, S.; Jiang, X. Impacts of human activities on coastal ecological environment during the rapid urbanization process in Shenzhen, China. *Ocean Coast. Manag.* **2018**, *154*, 121–132. [CrossRef]
57. Garland, G.; Banerjee, S.; Edlinger, A.; Miranda Oliveira, E.; Herzog, C.; Wittwer, R.; Philippot, L.; Maestre, F.T.; van Der Heijden, M.G. A closer look at the functions behind ecosystem multifunctionality: A review. *J. Ecol.* **2021**, *109*, 600–613. [CrossRef]
58. Carlucci, M.B.; Brancalion, P.H.; Rodrigues, R.R.; Loyola, R.; Cianciaruso, M.V. Functional traits and ecosystem services in ecological restoration. *Restor. Ecol.* **2020**, *28*, 1372–1383. [CrossRef]
59. Jalkanen, J.; Toivonen, T.; Moilanen, A. Identification of ecological networks for land-use planning with spatial conservation prioritization. *Landsc. Ecol.* **2020**, *35*, 353–371. [CrossRef]
60. Bibri, S.E.; Krogstie, J.; Kärrholm, M. Compact city planning and development: Emerging practices and strategies for achieving the goals of sustainability. *Dev. Built Environ.* **2020**, *4*, 100021. [CrossRef]
61. Almenar, J.B.; Elliot, T.; Rugani, B.; Philippe, B.; Gutierrez, T.N.; Sonnemann, G.; Geneletti, D. Nexus between nature-based solutions, ecosystem services and urban challenges. *Land Use Policy* **2021**, *100*, 104898. [CrossRef]
62. Soininen, J.; Bartels, P.I.A.; Heino, J.; Luoto, M.; Hillebrand, H. Toward more integrated ecosystem research in aquatic and terrestrial environments. *BioScience* **2015**, *65*, 174–182. [CrossRef]
63. d'Alcalà, M.R. Similarities, differences and mechanisms of climate impact on terrestrial vs. marine ecosystems. *Nat. Conserv.* **2019**, *34*, 505–523. [CrossRef]
64. Prampolini, M.; Savini, A.; Foglini, F.; Soldati, M. Seven good reasons for integrating terrestrial and marine spatial datasets in changing environments. *Water* **2020**, *12*, 2221. [CrossRef]

land

MDPI

Article

Spatio-Temporal Analysis of Green Infrastructure along the Urban-Rural Gradient of the Cities of Bujumbura, Kinshasa and Lubumbashi

Henri Kabanyegeye [1,2], Nadège Cizungu Cirezi [2,3], Héritier Khoji Muteya [2,4], Didier Mbarushimana [5], Léa Mukubu Pika [2], Waselin Salomon [2,6], Yannick Useni Sikuzani [4], Kouagou Raoul Sambieni [7,8], Tatien Masharabu [1] and Jan Bogaert [2,*]

1 Research Centre of Natural and Environmental Sciences, University of Burundi, Bujumbura P.O. Box 2700, Burundi; henri.kabanyegeye@ub.edu.bi (H.K.); tatien.masharabu@ub.edu.bi (T.M.)
2 Gembloux Agro-Bio Tech, University of Liège, Passage des Déportés 2, 5030 Gembloux, Belgium; n.cirezi@doct.uliege.be (N.C.C.); khoji.muteya@unilu.ac.cd (H.K.M.); lea.mukubu@student.uliege.be (L.M.P.); waselin.salomon@ueh.edu.ht (W.S.)
3 Department of Environment and Land Resources Management, Faculty of Agricultural Sciences and Environment, Evangelical University in Africa, Bukavu P.O. Box 3323, Democratic Republic of the Congo
4 Ecology, Ecological Restoration and landscape Research Unit, Faculty of Agricultural Sciences, University of Lubumbashi, Lubumbashi P.O. Box 1825, Democratic Republic of the Congo; sikuzaniu@unilu.ac.cd
5 Burundian Office for Environmental Protection, Bujumbura P.O. Box 2757, Burundi; mbardi05@gmail.com
6 Henri Christophe Campus in Limonade, State University of Haiti, Rte Nationale #6 Limonade, Limonade 1130, Haiti
7 Post-University Regional School of Integrated Planning and Management of Tropical Forests and Territories (ERAIFT), University of Kinshasa, Kinshasa BP 15373, Democratic Republic of the Congo; krsambieni@uliege.be
8 Faculty of Architecture, University of Lubumbashi, Lubumbashi BP 1825, Democratic Republic of the Congo
* Correspondence: j.bogaert@uliege.be; Tel.: +32-473-86-32-65

Citation: Kabanyegeye, H.; Cirezi, N.C.; Muteya, H.K.; Mbarushimana, D.; Mukubu Pika, L.; Salomon, W.; Useni Sikuzani, Y.; Sambieni, K.R.; Masharabu, T.; Bogaert, J. Spatio-Temporal Analysis of Green Infrastructure along the Urban-Rural Gradient of the Cities of Bujumbura, Kinshasa and Lubumbashi. *Land* **2024**, *13*, 1467. https://doi.org/10.3390/land13091467

Academic Editors: Luca Battisti, Fabrizio Aimar and Federico Cuomo

Received: 23 July 2024
Revised: 20 August 2024
Accepted: 28 August 2024
Published: 10 September 2024

Abstract: This study analyses the dynamics of green infrastructure (GI) in the cities of Bujumbura, Kinshasa, and Lubumbashi. A remote sensing approach, combined with landscape ecology metrics, characterized this analysis, which was based on three Landsat images acquired in 2000, 2013, and 2022 for each city. Spatial pattern indices reveal that GI was suppressed in Bujumbura and Kinshasa, in contrast to Lubumbashi, which exhibited fragmentation. Furthermore, the values of stability, aggregation, and fractal dimension metrics suggest that Bujumbura experienced rather intense dynamics and a reduction in the continuity of its GI, while Kinshasa showed weaker dynamics and tendencies towards patch aggregation during the study period. In contrast, Lubumbashi exhibited strong dynamics and aggregation of its GI within a context of significant anthropization. The evolution of the Normalized Difference Vegetation Index demonstrates a sawtooth pattern in the evolution of tall vegetation patches in Bujumbura, compared to a gradual decrease in Kinshasa and Lubumbashi. It is recommended that urban growth in these cities should be carefully planned to ensure the integration of sufficient GI.

Keywords: spatial analysis; remote sensing; fragmentation; green infrastructure

1. Introduction

With its urban population increasing from 27 million to 567 million between 1950 and 2015, Africa is currently the world's most rapidly urbanizing region [1]. The urban population of sub-Saharan Africa is the fastest-growing of all developing regions, followed by South and Central Asia [2]. This accelerating urbanization presents several environmental challenges, especially in Africa, thereby contributing to the development of urban ecology.

In this region, wars, natural population growth, and mass migration from rural areas to cities remain significant trends, leading to the expansion of ever-larger cities that are often adequately equipped to accommodate new inhabitants [3]. The spatial expansion of the town of Kampala in Uganda, where the urbanized area has increased fivefold from 71 km^2 in 1989 to 386 km^2 in 2010, is a striking example [4]. In Mozambique and South Sudan, high levels of urbanization have also occurred as a consequence of civil wars [5,6]. These new urban residents often move into underprivileged, informal neighborhoods that are unhealthy and lack basic infrastructure and services within the context of unplanned urban growth that has prevailed in sub-Saharan cities since the 1950s [4,7].

This lack of planning generally leads to the formation of social ghettos, the reinforcement of social inequalities, and the visual degradation of landscapes [8]. Green elements and formations in urbanized environments (such as urban trees, green belts, and other peri-urban forests) are becoming increasingly important for sustainable development [4] due to their multifunctionality [9]. Consequently, understanding the ecological functioning of urban ecosystems, particularly in tropical regions, has become a crucial area of research.

Although urban green infrastructure (GI) and its ecosystem services [10] are often conceptualized from a predominantly Western perspective of cities and their social, economic, and environmental challenges [11], studies of urban GI in sub-Saharan cities and their ecological functions have already been conducted [12]. Examples include the comparison of the GI of the towns of Bahir Dar and Hawassa [13] and the cities of Bamako and Sikasso [14], as well as the characterization of fruit tree diversity in the cities of Lubumbashi and Kolwezi [15]. However, isolated studies of individual cities do not always allow pertinent comparisons that would enable the development of large-scale regional or even supranational policies due to the application of different methodological approaches and non-standardized data sets.

Despite these methodological issues and the differing ecological, social, and economic contexts, comparative analyses of GI that extend beyond regional and sub-regional scales are valuable for formulating general conclusions that are not confined to a particular city [16,17]. In this context, a comparison of the GI of five different urban areas, including Cape Town, Durban, and Johannesburg in South Africa, and Birmingham and London in the UK, was undertaken [17]. This study examined how GI concepts were integrated into the decision-making processes of these cities. The pivotal role of GI in urban planning was confirmed by [18] for southern and eastern Africa. Similarly, [17] emphasizes the need for local governments to incorporate GI in development and climate adaptation strategies. Thus, comparative studies are justified to better understand and theorize the dynamics of tropical cities and the role of GI within them.

This study compares the GI of the cities of Bujumbura, Kinshasa, and Lubumbashi. Although these three cities have distinct socio-economic, demographic, morphological, and political contexts, they share certain commonalities. Firstly, they were all founded during the colonial era and are characterized by rapid demographic growth, reinforced by rural exodus and migrations due to political instability [19]. Additionally, their development is marked by increasing anthropogenic pressure on GI, resulting from a lack of urban planning [20], and by considerable population densities, estimated in 2023 at 11,686, 1730, and 3764 inhabitants per square kilometer for Bujumbura, Kinshasa and Lubumbashi, respectively. These cities were also selected because of the availability of studies on their ecosystems, which can be illustrated by several examples. For Bujumbura, data on floristic diversity and ecosystem services are available [21]. The typology, spatial structure, plant composition, management practices, state of maintenance, and ecosystem services of GI in the city of Kinshasa have already been analyzed [22]. For Lubumbashi, studies concerning the spatial pattern of GI along the urban-rural gradient [23], the perception by local experts of GI and their ecosystem services [24,25], and the diversity of street-lining trees [26] are available. In addition, peri-urban areas have been intensively described with regard to their tree and shrub vegetation [27]. Despite these individual studies, no comparative study has yet been conducted to identify commonalities between the GI of these three cities.

The aim of this study is to provide a spatio-temporal analysis of the GI of the cities of Bujumbura, Kinshasa, and Lubumbashi from 2000 to 2022, using remote sensing and spatial pattern indices. The central hypothesis posits that while the GI in each of these three cities is undergoing a unique dynamic, it is also characterized by common trends such as the regression of vegetation, an increasing prevalence of herbaceous vegetation, a rise in the level of anthropization, and a decrease in the spatial continuity of the GI. This hypothesis is subdivided into three sub-hypotheses: (i) the GI in all three cities exhibits significant instability and a regressive surface trend, particularly in favor of built-up areas, (ii) the GI of all cities shows an increasing level of anthropization and a decreasing level of spatial continuity over time, (iii) each city demonstrates a specific dynamic in the composition of the GI in terms of low (herbaceous) and high (tree) vegetation that is specific to it, yet with a common trend towards the dominance of lower biomass in GI.

2. Materials and Methods

2.1. Study Area

This study was conducted in three cities: Bujumbura, Kinshasa, and Lubumbashi (Figure 1). The city of Bujumbura was founded in 1897 on the shores of Lake Tanganyika by the Germans on a site called Kajaga. It is situated in the western part of the Republic of Burundi, between 3°30′ and 3°51′ S and 29°31′ and 29°42′ E. Bujumbura covers 10,462 hectares and comprises three communes (Table 1), which are subdivided into 13 administrative entities. These entities are set up as urban areas. The city-province of Kinshasa, founded in 1881 by explorer and journalist Henry Morton Stanley on the southern bank of the Pool Malebo, is located in the western part of the Democratic Republic of Congo, between 4° and 5° S and 15°–16° E, and covers an area of 9965 km^2. Since 1968, it has been administratively subdivided into 24 communes (Table 1). For this study, the rural commune of Maluku was excluded from the analyses, not only because of its size (it alone covers an area of 82.8% of the entire city of Kinshasa) but also because of the lack of cloud-free multi-temporal images [28]. The city of Lubumbashi and its outskirts are located in the province of Haut-Katanga in the southeastern part of the Democratic Republic of Congo. It covers an area of almost 747 km^2 and is located between 11°27′ and 11°47′ S and 27°19′ and −27°40′ E, and it comprises 7 communes. The town was created in 1910 following the discovery and development of large copper deposits by the Haut-Katanga Mining Union (HKMU) and is the capital of Haut-Katanga province (Table 1).

Table 1. Characteristics of the cities of Bujumbura, Kinshasa, and Lubumbashi.

	Bujumbura	**Kinshasa**	**Lubumbashi**
Year of creation	1897	1881	1910
Location	Between 3°30′ and 3°51′ S and 29°31′ and 29°42′ E	Between 4° and 5° S and 15° and 16° E	Between 11°27′ and 11°47′ S and 27°19′ and −27°40′ E
Area	10,462 hectares	9965 km^2	747 km^2
Number of communes	3	24	7
Population	1,225,142 residents	170,329,463 residents	2,812,000 residents

2.2. Selection of Satellite Images

The cities of Bujumbura, Kinshasa, and Lubumbashi were each isolated by three 30 m resolution Landsat images acquired and processed on the Google Earth Engine (GEE) geospatial platform. The median images were obtained by selecting the median values of each pixel during the dry season from June to August. Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and Landsat 8 Operational Land Imager (OLI) sensors were used to obtain images from 2000, 2013, and 2022, respectively. The choice of years and intervals was guided by three primary factors. Firstly, the city of Bujumbura underwent urbanization without planning and management tools between 2000 and 2015. It was only from 2015 to 2023 that an urban master plan was developed, outlining a vision for the city up to 2045. Secondly, for the cities of Kinshasa and Lubumbashi, the period from

2000 to 2010 was largely influenced by the liberalization of the mining sector (2002), the first electoral cycle (2006), infrastructure modernization, and the global financial crisis (2008). The period from 2010 to 2022 included further electoral cycles (2011 and 2018), provincial restructuring (2015), and a change in political regime (2019) [29]. Thirdly, the city of Kinshasa is characterized by persistent heavy cloud cover, which limits the availability of satellite imagery. This constraint led us to consider only three specific dates, which we believe are sufficient to understand the phenomenon of urbanization in the cities studied, considering the availability of imagery for these periods. We used surface reflectance data from the Level 2 Collection 2 Tier 1 datasets, collected over a time step of 13 and 9 years, depending on availability, quality, and study objectives. The image acquisition period corresponds to the dry season when cloud cover is low [30]. The training points collected on the GEE platform were supplemented by ground truth points collected jointly in the 3 cities in July 2022. For each class, a total of 20 GPS coordinates were collected, yielding a maximum of 180 GPS points. Additionally, the results for our final year (2022) were compared with those provided by the ESRI_Global-LULC_10m_TS project in for the three cities. The consistency in trends across the results provided reassurance of the credibility of our findings. ArcGIS 10.8.1 software was then used to produce land-use maps.

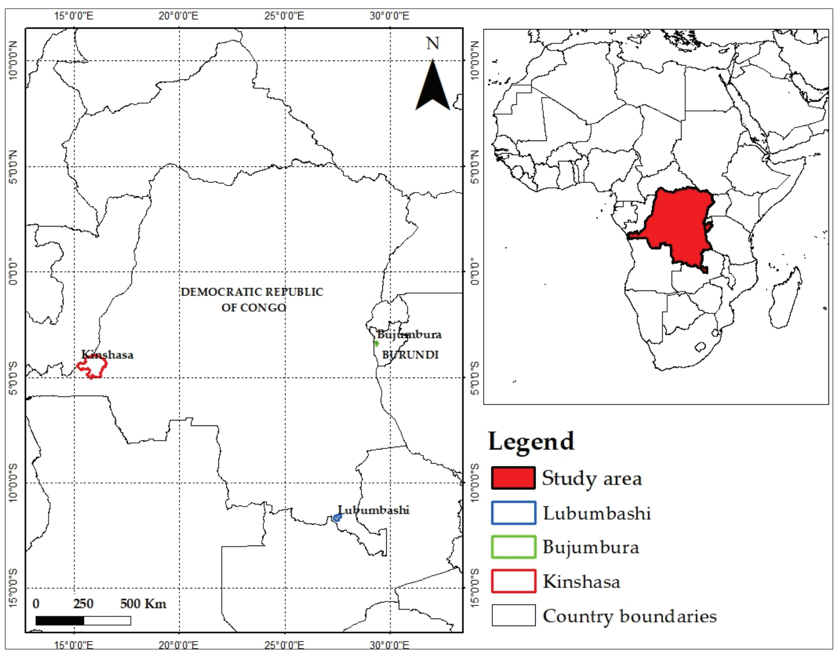

Figure 1. Bujumbura is located in Burundi and Kinshasa, and Lubumbashi is in the Democratic Republic of the Congo.

2.3. Image Pre-Processing, Processing and Classification

The pre-processing involved applying a cloud mask applied to each data set to create a synthetic image with an acceptable cloud cover [31]. The mask used the "QA_PIXEL" band and the Fmask (Function of mask) algorithm to remove clouds and cloud shadows, thereby generating cloud-free composites [32,33].

A false-color composition was created by combining the near-infrared, red, and green bands, with the first two channels being used to discriminate vegetation [34]. Three relevant land cover classes were selected according to the study's objectives and the composition of each landscape: vegetation (forests, savannahs, fields, fallow lands, and green spaces), built-up and bare soil (built-up and bare soil complexes, including mines) and other (sewage and decantation plants, flooded areas, ponds, swamps). For each of these land cover classes, sample polygons representing the training zones (ROIs) were collected on the same platform (GEE) using Google Earth images of finer resolution (1 m) and completed with ground truth GPS points. A classification based on the "Random Forest" supervised classification algorithm was then performed using the training model obtained from the selected ROIs [35]. Classifications were validated based on the overall accuracy and the Kappa coefficient derived from six confusion matrices [36]. Kappa values below 50%, between 50 and 75%, and above 75% indicate poor, acceptable, and excellent classification, respectively [37]. For each land cover, at least 30% of the total points were used for this assessment.

2.4. Calculation of Spatial Pattern Indices and Detection of Landscape Dynamics

Pattern metrics for each land use class were calculated using the "landscape metrics" and "Landscape tools" packages in R studio 4.2.2. The selected indices provide information on landscape fragmentation [38]. The number of patches belonging to a given class $j(n_j)$. This index offers insight into the fragmentation of a class. A high number of patches in a class may be due to its fragmentation [39]. The total area (a_{tj}) occupied by the class j (in km^2) was calculated according to Equation (1) where a_{ij} is the area of ith patch of class j:

$$a_{tj} = \sum_{i=1}^{n_j} a_{ij} \quad (1)$$

The index of the largest patch of class j or dominance $D_j(a)$ was calculated using the area of the largest patch ($a_{max,j}$):

$$D_j(a) = \frac{a_{max,j}}{a_{tj}} \times 100 \quad (2)$$

with $0 < D_{j(a)} \leq 100$. The higher the dominance value, the less fragmented the class.

The average area $\bar{a}_j$ of the patches of class j was calculated as follows:

$$\bar{a}_j = \frac{a_{tj}}{n_j} \quad (3)$$

The aggregation index indicates the frequency with which pairs of patches of the same class are adjacent [40]. Its value is equal to 0 for maximally disaggregated classes and 100 for maximally aggregated classes [41]:

$$\left[\frac{g_{ii}}{max - g_{ii}}\right] \times (100) \quad (4)$$

where g_{ii} is the number of similar adjacencies based on the single count method and $max - g_{ii}$ is the maximum number of similar adjacencies per class for this class.

The fractal dimension index, which assesses the relationship between the landscape transformation process and the geometry of the resulting patches, is calculated as follows according to [42]:

$$\log P = \frac{D}{2\log(A) + \log(K)} \quad (5)$$

where p represents the perimeter, A the class area, and D the fractal dimension. A log-log surface-perimeter plot for a set of patches, therefore, generates D (slope) and K (intercept). This technique is based on the analysis of patches of different sizes at a given scale as a "surrogate" for a change of scale [43].

To quantify the dynamics of conversion between land-use classes over the periods considered in the study, two transition matrices were created for each city. The transition matrix, obtained by juxtaposing the land-use maps, provides information on the conversion between land uses (row and column proportions) on the one hand and the stability of land use classes (diagonal) on the other [38]. The stability index was calculated to determine the conversions between the different land-use classes. This index is defined as the ratio of the sum of the diagonal values and the sum of the off-diagonal values of the transition matrix [38]. The underlying spatial transformation processes responsible for the observed changes were identified using the decision tree proposed by [44]. The distinction between fragmentation and dissection was made using the predefined area decrease value $t = 0.75$ [45]. Values less than or equal to 0.75 indicate fragmentation, while values greater than 0.75 suggest dissection [45].

The aggregation index (AI), which illustrates the spatial organization of patches corresponding to land use types, was also calculated. A high AI value indicates adjacent units and, therefore, aggregated patches [46].

The other index calculated is the fractal dimension index (DF), which indicates that the patches have complex shapes and more tortuous contours when it is higher (approaching 2) and when it is lower (close to 1); this indicates a more regular shape of the patches and smoother contours (anthropogenic) [43].

2.5. Vegetation Index

A variety of vegetation indices have been developed for the purpose of monitoring vegetation distribution and phenology [47,48]. The Normalized Difference Vegetation Index (NDVI) is defined as the normalized difference of spectral reflectance measurements acquired in the "Near Infrared (NIR)" and "Red (RED)" wavelength zones [47–49].

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \tag{6}$$

The theoretical value of NDVI varies between −1 and 1. Values below 0.1 are indicative of bodies of water and bare soil, while higher values are associated with high photosynthetic activity, which is typical of shrublands, temperate forests, rainforests, and agricultural land [50]. In practice, an open water surface (ocean, lake, etc.) will exhibit NDVI values close to 0, bare soil will have values of 0.1 to 0.2, while dense vegetation will have values of 0.5 to 0.8 [50].

3. Results

3.1. Satellite Data Analysis: Classification and Mapping (2000 to 2022)

The overall accuracy of supervised classification of Landsat images covering the areas of Bujumbura, Kinshasa, and Lubumbashi ranges between 89% and 99%, with Kappa values between 69% and 97% (Table 2). These values indicate that the discrimination between different land-use classes is statistically reliable [51].

Table 2. Accuracy of supervised classifications of Landsat images from 2000, 2013, and 2022 based on the Random Forest algorithm.

Year	Bujumbura		Kinshasa		Lubumbashi	
	Overall Accuracy	Kappa	Overall Accuracy	Kappa	Overall Accuracy	Kappa
2000	0.89	0.69	0.95	0.86	0.95	0.92
2013	0.93	0.79	0.97	0.88	0.96	0.94
2022	0.97	0.91	0.99	0.94	0.98	0.97

A visual analysis of the land-use maps reveals significant spatial changes in the landscape of Bujumbura and Lubumbashi between 2000, 2013, and 2022. These changes are evidenced by a regression of the "vegetation" class and the "other" class, which have been replaced by the "built-up" class. In contrast, the city of Kinshasa exhibited minimal change (Figure 2).

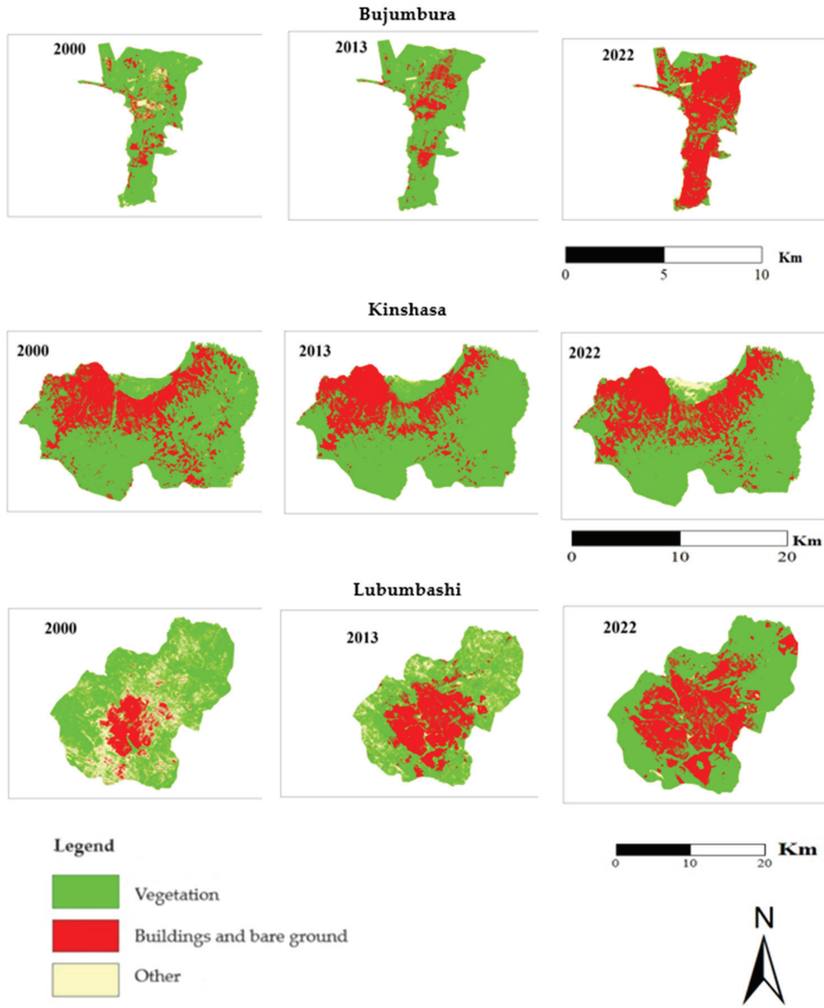

Figure 2. Land use maps of Bujumbura (Burundi), Kinshasa, and Lubumbashi (DRC) from supervised classification of Landsat images from 2000, 2013, and 2022 based on the Random Forest algorithm.

3.2. Changes in Land Use between 2000 and 2022

Table 3 illustrates the percentage changes between the various land use classes between the years 2000 and 2022 in the cities of Bujumbura, Kinshasa, and Lubumbashi. In the cities of Bujumbura and Lubumbashi, the period studied (2000–2022) was characterized by a transition in which the GI, which constituted the landscape matrix in 2000, was replaced by built-up areas, which became the dominant matrix in 2022. During the period under review, the landscape of Kinshasa underwent no significant modifications, and its GI remained the dominant matrix in 2022 (Table 3).

Table 3. The following transition matrix describes the changes in land use in the cities of Bujumbura (Burundi), Kinshasa, and Lubumbashi (DRC) between the periods 2000–2013 and 2013–2022 in percentages of area (%). The column and row totals correspond to the land-use classes for the initial and subsequent study periods, respectively. The values in bold represent the proportion of the urban footprint that has not undergone transformation between the two specified time points. The remaining values within the matrix provide insight into the nature of the observed changes in land use.

Bujumbura		**Year 2013**			
		Vegetation	**Buildings and Bare Ground**	**Other**	**Total**
Year 2000	Vegetation	**9.78**	47.51	0.36	57.65
	Buildings and bare ground	30.42	**5.01**	0.05	35.48
	Other	4.38	1.90	**0.59**	6.87
	Total	44.58	54.42	1.00	100
		Year 2022			
Year 2013	Vegetation	**18.17**	26.36	0.06	44.58
	Buildings and bare ground	1.69	**52.17**	0.56	54.42
	Other	0.04	0.37	**0.58**	1.00
	Total	19.90	78.90	1.20	100
Kinshasa		**Year 2013**			
Year 2000	Vegetation	**58.31**	6.70	0.46	65.47
	Buildings and bare ground	11.17	**21.94**	0.03	33.14
	Other	1.12	0.06	**0.21**	0.39
	Total	70.60	28.70	0.70	100
		Year 2022			
Year 2013	Vegetation	**60.78**	8.28	1.54	70.60
	Buildings and bare ground	3.86	**24.80**	0.04	28.70
	Other	0.28	0.02	**0.40**	0.71
	Total	64.92	33.10	1.99	100
Lubumbashi		**Year 2013**			
Year 2000	Vegetation	**30.85**	17.75	21.65	70.25
	Buildings and bare ground	1.13	**12.75**	275	16.63
	Other	3.46	4.67	**4.99**	13.12
	Total	35.44	35.17	29.39	100
		Year 2022			
Year 2013	Vegetation	**18.91**	7.55	8.98	35.44
	Buildings and bare ground	1.89	**30.92**	2.36	35.17
	Other	5.46	15.50	**8.43**	29.39
	Total	26.26	53.97	19.77	100

For the city of Bujumbura, the period from 2000 to 2013 was marked by a 47.52% increase in built-up and bare soil at the expense of vegetation. The same period was characterized by the conversion of 30.42% of built-up and bare ground and 4.38% of the "other" class to vegetation. At the same time, areas in the "other" class decreased by 1.9% in favor of built-up and bare ground. Between 2013 and 2022, built-up and bare ground expanded by 26.36% at the expense of vegetation. At the same time, 1.69% of built-up and bare ground was converted to vegetation.

The period between 2000 and 2013 was characterized by a significant increase in built-up and bare soil areas in the city of Bujumbura, with a 47.52% expansion at the expense of vegetation. The same period was characterized by the conversion of 30.42% of built-up and bare ground, as well as 4.38% of the "other" category, to vegetation. Concurrently, the "other" category experienced a 1.9% reduction in area with an increase in built-up and bare ground. Between 2013 and 2022, built-up and bare ground expanded by 26.36% at the expense of vegetation. Concurrently, 1.69% of built-up and bare ground was converted to vegetation.

Regarding the city of Lubumbashi, between the years 2000 and 2013, 1.08% of buildings and bare soil and 3.44% of other areas were converted to accommodate vegetation. Conversely, 17.9% of built-up and bare ground and 21.65% of the "other" category expanded at the expense of vegetation. Concurrently, the "other" category exhibited an increase of 7.75% at the expense of built-up and bare ground. The period between years 2013 and 2022 is characterized by the conversion of 1.88% of built-up and bare ground, 5.48% of other to vegetation, and 15.5% of the "other" class to built-up and bare ground. During the same period, 7.54% of the built-up area and soil and 8.97% of the "other" class were converted to vegetation. Concurrently, 2.36% of the "other" class was converted to bare ground and buildings.

The preceding data illustrate a notable decline in GI and an accompanying surge in the surface area of built-up and bare soil within the urban cores of Bujumbura and Lubumbashi between the years 2000 and 2022. In the case of Kinshasa, there was a slight decrease in GI but no increase in the surface area of built-up and bare soil. However, there was an increase in the "other" class. A sequence of progression/regression of vegetated surfaces was recorded.

Table 4 illustrates the stability index values for land use classes in the cities of Bujumbura, Kinshasa, and Lubumbashi between the years 2000 and 2022. This index exhibits high values in landscapes that have undergone minimal dynamic change.

Table 4. Stability index for the vegetation, built-up, and bare soil classes as well as the "other" class for the cities of Bujumbura (Burundi), Kinshasa, and Lubumbashi (DRC) over the period 2000 to 2022.

		Bujumbura	**Kinshasa**	**Lubumbashi**
2000–2013	Vegetation	0.12	3.00	0.70
	Buildings and bare ground	0.06	1.22	0.41
	Other	0.09	0.13	0.13
2013–2022	Vegetation	0.65	4.35	0.79
	Buildings and bare ground	1.80	2.03	1.13
	Other	0.56	0.21	0.26

Over the period 2000–2013, the vegetation stability index for Kinshasa is 25 times that of Bujumbura and 4 times that of Lubumbashi. Over the same period, the value of the stability index for buildings and bare soil in Kinshasa was 20 times that of Bujumbura and 3 times that of Lubumbashi. Furthermore, the stability index for the "other" category is identical for the cities of Kinshasa and Lubumbashi and is 1.5 times that of Bujumbura.

From 2013 to 2022, the vegetation stability index for Kinshasa was sevenfold that of Bujumbura and 5.5 times that of Lubumbashi. Over the same period, the stability index for buildings and bare soil in Kinshasa was found to be twofold that of Bujumbura and Lubumbashi. Conversely, the stability index for the "other" class in Bujumbura was three times that of Kinshasa and Lubumbashi.

From the aforementioned data, it can be observed that vegetation, buildings, and bare soil in the city of Kinshasa exhibited minimal change over the period 2000–2022. In contrast, the "other" class demonstrated robust growth in all cities (Table 4).

3.3. Dynamics of the Spatial Structure of Vegetation

In Bujumbura, between 2000 and 2013, the characteristic spatial transformation process of vegetation was the dissection of patches, particularly as the increase in the number of patches was accompanied by a decrease in total area, with a t-value greater than 0.75.

From 2013 to 2022, the characteristic spatial transformation process of vegetation was identified as suppression, which was observed concurrently with a reduction in the number of patches and total area. Between 2000 and 2022, the values assigned to vegetation dominance increased, indicating the presence of undeveloped vegetation areas on the city's periphery that had not yet been developed. The Aggregation Index (AI), which reflects the spatial organization of patches, showed a 6.96% decline over the study period. The fractal dimension (FD) approached a value of 1, suggesting a reduction in spatial continuity and an increase in anthropization over time.

Between the years 2000 and 2013, the vegetation in the city of Kinshasa exhibited a distinctive pattern characterized by patch aggregation. This was evidenced by a significant increase in the total area of vegetation, which was the result of a simultaneous decrease in the number of patches. From 2013 to 2022, the process of spatial transformation of vegetation was suppressed due to a decrease in both the total area and the number of patches. Over the period 2000 to 2022, the values of vegetated area dominance exhibited a slight decline. The aggregation index demonstrated an increase of 1.72% over the period 2000 to 2022, and the fractal dimension reached 1.04. This indicates a high level of vegetation dominance, which is indicative of a slight increase in spatial continuity and a notable rise in anthropization over time.

In Lubumbashi, the dominant spatial transformation process of vegetation between 2000 and 2013 was suppression, characterized by a simultaneous decrease in both the total area and the number of patches. From 2013 to 2022, the characteristic spatial transformation of vegetation was dissection, with a concomitant increase in the number of patches despite a decrease in total patch area. Between 2000 and 2022, the value of vegetation dominance declined, indicating its gradual disappearance due to anthropogenic influence. The AI demonstrated an increase of 7.77% over the study period. The FD is close to 1, which suggests an increasing level of spatial continuity and anthropization over time (Table 5).

Table 5. Spatial structure indices were calculated in 2000, 2013, and 2022 of the vegetation class for the cities of Bujumbura (Burundi), Kinshasa, and Lubumbashi (DRC). These indices enable the identification of the underlying spatial transformation processes that have resulted in the observed changes. The data were derived from the supervised classification of Landsat images using the Random Forest algorithm. n: number of patches, a_t: total area (ha), $\overline{a}_j$: average area, D: dominance index of the largest patch (%), FD: fractal dimension, AI: aggregation index.

City	Year	n	a_t	D	$\overline{a}_j$	AI	FD
Bujumbura	2000	1246	6032.39	1.55	1.45	92.47	1.04
	2013	1349	4665.01	5.15	1.79	91.99	1.04
	2022	1007	2081.94	3.36	1.62	86.03	1.04
Kinshasa	2000	7704	652,209.25	57.47	15.36	92.80	1.04
	2013	4623	703,429.35	63.49	27.61	95.50	1.04
	2022	6685	646,828.15	56.57	17.56	94.40	1.04
Lubumbashi	2000	6925	55,453.28	47.12	8.00	85.46	1.04
	2013	5386	28,034.65	10.77	5.20	83.30	1.04
	2022	11,173	20,904.10	15.96	1.87	92.10	1.04

Figure 3 shows the evolution of the spatial structure indices calculated for the vegetation class of the cities of Bujumbura, Kinshasa, and Lubumbashi for the years 2000, 2013, and 2022.

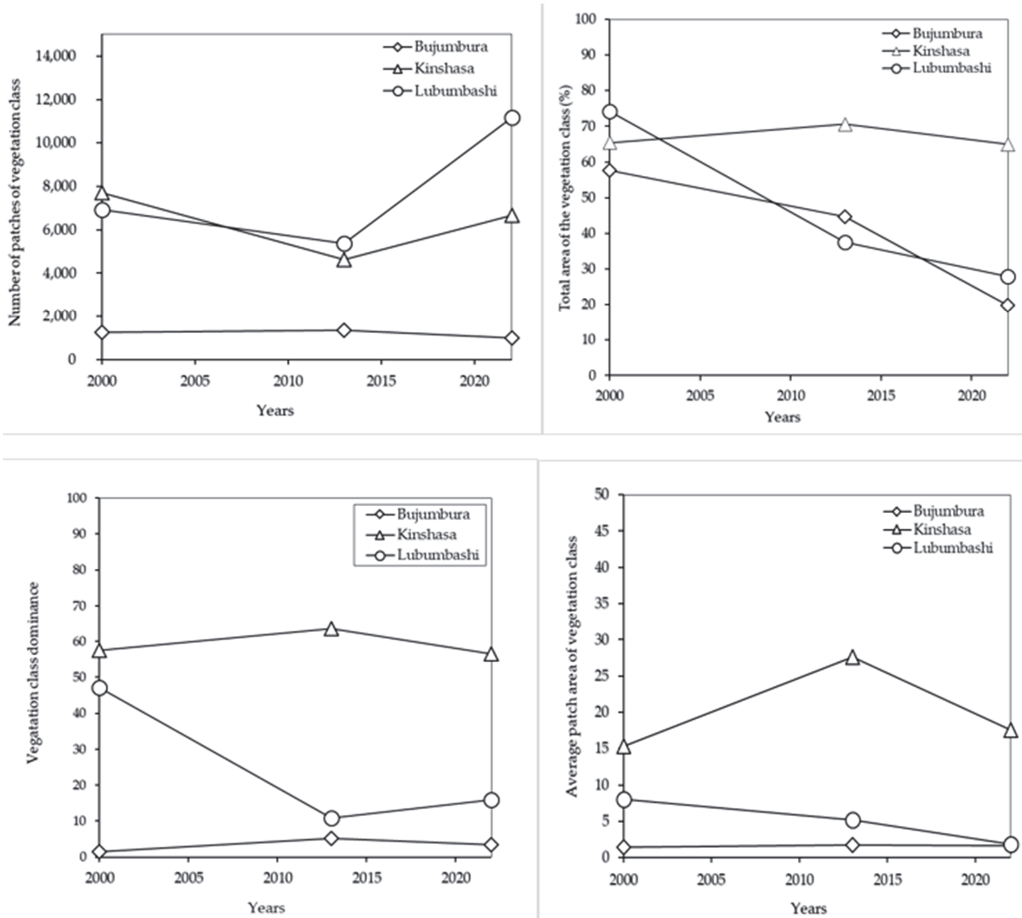

Figure 3. Trends in number of patches, total area, average patch area, and vegetation class dominance for the cities of Bujumbura (Burundi), Kinshasa, and Lubumbashi (DRC) for the years 2000, 2013, and 2022.

3.4. The Normalized Difference Vegetation Index (NDVI)

The maps generated after calculating the Normalized Difference Vegetation Index (NDVI) for the years 2000, 2013, and 2022 show that the values range from −0.22 to 0.85 for Bujumbura, from −0.21 to 0.92 for Kinshasa (DRC) and from −0.50 to 0.83 for Lubumbashi (DRC) (Figure 4).

Figure 5 illustrates the proportions of GI areas across the NDVI intervals identified for each city under study during the specified time periods of 2000, 2013, and 2022. The evolution of tall vegetation in Bujumbura shows a sawtooth pattern, whereas in Kinshasa and Lubumbashi, there is a gradual decline.

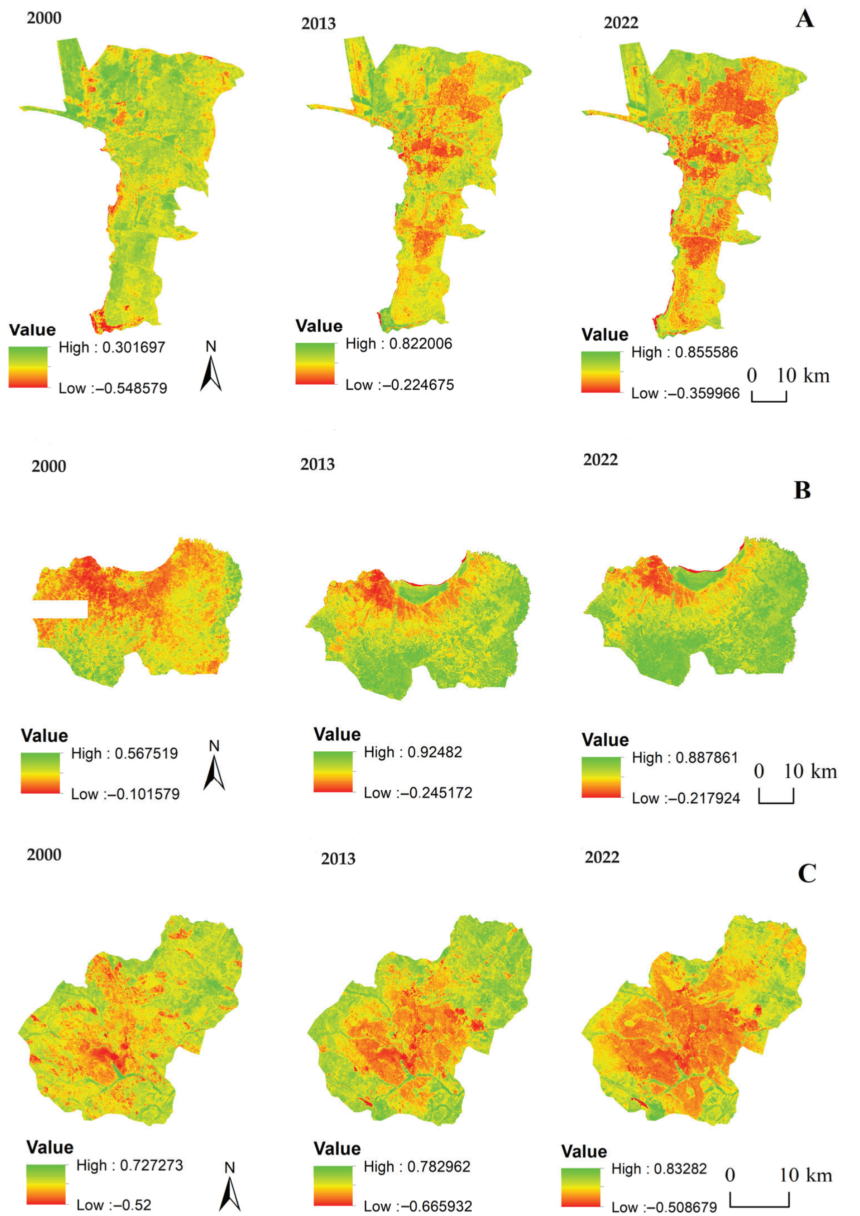

Figure 4. Normalized difference vegetation maps of the cities of Bujumbura (Burundi) (**A**), Kinshasa (**B**), and Lubumbashi (DRC) (**C**) for the years 2020, 2013, and 2022.

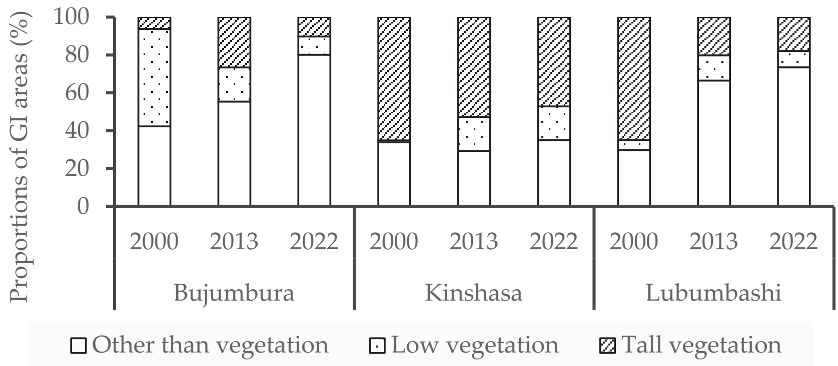

Figure 5. Proportions of GI areas over NDVI intervals were found for the cities of Bujumbura, Kinshasa, and Lubumbashi for the years 2000, 2013, and 2022.

4. Discussion

4.1. Methodological Approach

While Landsat images are not optimal for examining urbanized landscapes, where a single pixel may encompass disparate land uses, they have nonetheless enabled the fulfillment of the study's objective through the consolidation of land use classes. It is also noteworthy that these images are frequently employed for the mapping of urban landscapes in sub-Saharan Africa [20]. Moreover, any approach to classifying satellite images must be based on knowledge of the reality of field observations, which helps to mitigate the degree of confusion between thematically similar pixels [52]. Based on in situ knowledge acquired during field missions, old maps, Google Earth images, and processing on the GEE platform, Kappa values are among the classifications deemed acceptable and excellent in this study [38]. Furthermore, the indices selected in this study, including the number and area of patches, are considered optimal compromises for characterizing landscape configuration [52]. The utilization of the R language and its extensions (packages) was informed by the fact that, since its inception in 1995, it has currently one of the most prevalent programming languages, particularly within the field of ecology. Additionally, it is a language exclusively designed for statistical programming [53]. This methodology has been employed in other countries and contexts. In Rwanda, for instance, the methodology was employed to quantify the physical degradation of forests and to monitor forest cover change and fragmentation [54]. Furthermore, it has been employed for the spatial analysis of urban surface heat islands in four rapidly developing African cities (Ethiopia, Kenya, Nigeria, and Zambia) [55].

4.2. Spatial Structure Indices

Several indices have been put forth with the aim of quantifying and measuring landscape structure [56,57]. The calculation of spatial structure indices serves to elucidate the spatial configuration of class patches within the landscape [46]. It is thus possible to calculate a wide range of indices, although this may result in redundant measurements [46]. In this study, we used indices derived directly from fragmentation. In general, ecology and landscape ecology, in particular, habitat fragmentation, has emerged as a pivotal theme in conservation research [58]. Indeed, fragmentation results in a reduction in total area and an increase in the number of patches [39]. Furthermore, we considered the dominance of the largest patch in the class, as fragmentation implies fragmentation and, therefore, a decrease in patch size towards smaller patches of similar size [59]. The mean area value was employed as an indicator of spatial integrity [55]. The shape index was not considered in this study. Indeed, the quantification of shape is a challenging endeavor, as it can give rise to multiple interpretations [60]. Furthermore, it is linked to degrees of artificialization [61]. It is also associated with landscape heterogeneity [62]. It can be observed that the value of the shape index is inversely proportional to the degree of elongation or irregularity of the shapes of the patches [63]. In contrast, the fractal dimension index was employed. A higher index value (approaching 2) indicates more complex shapes and contours that are more tortuous and natural. Conversely, a low index value (close to 1) suggests a more regular shape and contours that are smoother and anthropogenic [43]. These indices have been used in various contexts to analyze the degree of anthropization of urban or forest landscapes, such as the characterization of dense forest islands in the Monts Kouffé classified forest with the aim of highlighting their spatio-temporal dynamics [59] as well as the quantification of the degenerating condition of the land cover due to anthropogenic activities in Katanga [64]. They were also employed to assess the anthropogenic impact on the dynamics of landscape units, including the quality of ecosystem services in the Kinshasa conurbation [22]. The aggregation index (AI) was also calculated in this study. This index illustrates the spatial organization of patches corresponding to land use types. A high AI value indicates the presence of adjacent units and, consequently, aggregated patches [46]. This index has been employed in other contexts, including the monitoring of landscape anthropization in the Babagulu forest region (DRC) [65] and the assessment of links between landscape elements, their reciprocal influences, and the main transformations observed over time and space for the rational and sustainable management of the Zè commune in Benin [46]. Additionally, this study utilized the stability index, which enables the evaluation of the permanence of the initial landscape [38] in diachronic studies. All these indices were used to test the first two sub-hypotheses of our research.

4.3. Standardized Differential Vegetation Index and Green Infrastructure Composition Dynamics

Spectral vegetation indices are among the most widely used satellite data products for assessments of vegetation cover, change, and processes [49]. The Normalized Difference Vegetation Index (NDVI) provides estimated values of forest "green intensity" based on the analysis of satellite data. The approach is based on the premise that NDVI is an indicator of plant health insofar as a degradation of an ecosystem's vegetation or a decrease in green intensity would result in a decrease in the NDVI value [50]. Consequently, NDVI values have been employed in a multitude of contexts, including the assessment of vegetation cover variability across Algeria [47], the observation of forest degradation in Mexico [66], the monitoring of climatic variability in the Nakambé watershed in Burkina Faso [67] and the establishment of the link between vegetation NDVI, temperature, and precipitation, in the upper catchments of the Yellow River in China [68]. In this study, the NDVI was calculated to facilitate a comparison of the health of GI in the cities of Bujumbura, Kinshasa, and Lubumbashi and to test our last sub-hypothesis. The NDVI values observed for the cities under investigation exhibited a range between -1 and 1, indicating that the GI of these cities is not solely comprised of vegetation at high and low levels but also includes other elements such as water bodies and soils devoid of water [50]. Indeed, Bujumbura's GI comprises a variety of elements, including artificial forests [69], GI adjacent to roads, playgrounds, green squares, and agricultural areas. Additionally, it encompasses bare soil, a consequence of land subdivision for new residential developments, particularly in the southern periphery of the city. Furthermore, since the 2020s, the rising waters of Lake Tanganyika have resulted in the formation of swamps in the western part of the coastal city situated on its shores. In addition to the GI that dates back to the pre-independence period, the city of Kinshasa also encompasses private GI, residential GI, swampy areas, and erosion expansion at the edge of watercourses [22]. Bare soils resulting from urbanization and slash-and-burn agriculture [22] are also noted. In addition to GI accompanying roads in the urban part and buffer zones, fields, abandoned areas, and informal spaces in peri-urban areas [22], the city of Lubumbashi also features bare surfaces resulting from mining, especially on the outskirts of the city. This presence can be attributed to the destruction of vegetation cover near mining sites, probably due to the developments carried out to establish mining sites [27]. The proportions of the surface areas of the various GI categories on the NDVI intervals demonstrate variability between cities over the period studied (2000–2023). This variability is evidenced by a sawtooth trend in tall vegetation for the city of Bujumbura and a gradual decrease for the cities of Kinshasa and Lubumbashi.

4.4. Urbanization and Loss of Natural Cover in the Cities of Bujumbura, Kinshasa and Lubumbashi

Urban vegetation plays an instrumental role in the provision of diverse ecosystem services, including the purification of air and water, the regulation of microclimate, and the treatment of waste [70]. Moreover, its presence offers people aesthetic pleasures, recreational opportunities, and physical and psychological well-being [71]. It is regrettable that the current rate of urbanization in developing countries [72] is accompanied by the elimination of GI and their replacement by anthropogenic land uses [73,74]. Cities such as Bujumbura in Burundi, Kinshasa, and Lubumbashi in the Democratic Republic of the Congo illustrate this phenomenon. Indeed, Bujumbura's urbanization is characterized by the conversion of agricultural land for the construction of new neighborhoods [75]. Furthermore, the expansion of the city is marked by the gradual destruction of GI and other natural ecosystems to make way for new housing and other physical infrastructure, including roads and monuments. Additionally, the vegetation in buffer zones along rivers and Lake Tanganyika has been cleared to accommodate residential development [69]. The urban growth of Kinshasa occurs through the aggregation of built-up areas, which has a detrimental impact on green zones, including residual GI and market gardens [76]. This results in two distinct patterns of urban growth: extreme densification of certain central districts and low-density peripheral extensions [76]. The city of Lubumbashi has experienced a similar expansionary trajectory, with the built-up area extending towards the peri-urban zone, where plot prices are relatively affordable compared to the city center [23]. The regression of GI in all communes has been caused by the combination of strong demographic pressure and the absence of a program to preserve them [24,26]. Our results illustrate the regression and fragmentation of urban vegetation as a result of urbanization. The phenomenon of urban vegetation regression in the wake of rapid and uncontrolled urban spatial growth has also been observed in other African cities, including Abuja in Nigeria [77], Kampala in Uganda [4], and in central Togo [78]. The removal of GI from the city of Bujumbura can be attributed to the emergence of subdivisions, particularly on the outskirts of the city, which have given rise to new neighborhoods. The increasing evolution of built-up and bare soil is thought to have contributed to the disappearance of GI in the city of Kinshasa. This is believed to have originated in the destruction of GI to satisfy the wood energy needs of artisanal pastry businesses and "nganda ntaba" (various corners where kebabs, chicken legs, and grilled goat meat are sold) on the one hand, and their use for various constructions on the other [79]. Additionally, the high consumption of wood energy by restaurants, brickmakers, bakeries, and blacksmiths is a contributing factor [79]. Regarding to the fragmentation of GI in the city of Lubumbashi, this is attributable to a combination of factors, including the city's rapid urbanization and the expansion of energy production [80]. Additionally, the fragmentation is a consequence of the patchwork nature of the city's GI, which comprises GI alongside roads in the urban area and buffer zones, fields, abandoned areas, and informal spaces in the peri-urban zones [23]. The urban expansion of the cities of Lubumbashi and Kinshasa and the resulting quest for wood energy are threatening the protected areas around these cities. In the city of Bujumbura, specifically, peri-urban agriculture is under threat.

4.5. Implications in Public Policy

In African cities, GI is still considered by the population and certain authorities in charge of urban planning secondary spaces that are merely decorative or spaces that are free of all occupation and passage [81]. In reality, however, it needs to be preserved and developed, hence the need for scientific assistance in the conservation and development of GI. Our results highlighted the decline in GI in the cities studied and a decrease in tall vegetation, all in the context of increasing anthropization. Indeed, for all the cities studied, urbanization is the primary cause of the reduction in their GI following the installation of new houses or other infrastructures such as monuments, the densification of neighborhoods, and peripheral extensions. This situation should attract the attention of municipal planners and decision-makers and involve a range of policies along the urbanization gradient [82]. These policies concern the legal security of GI and its integration into land use planning, as well as the planning of their management, maintenance, and control [83]. Law enforcement, transparency, reliability, and the absence of corruption are crucial elements for sustainable urbanization that incorporate the conservation of vegetated ecosystems and economic development in the city [2,84]. The demolition of infrastructure or other facilities built on GI should also be considered. In the (peri)urban area, avenue trees should be planted along the main roads running through it and should, above all, be included in the urban development plan for new neighborhoods. The new occupants of these neighborhoods should be made aware of planting trees on secondary roads running through their neighborhoods along their plots, in addition to landscaping them. Priority should be given to preserving and increasing the connectivity of the GI of the cities studied [85] and, above all, to encouraging the creation of GI for buildings and roads. All these cities should adopt a master plan for the sustainable integration of GI into the urban fabric as a matter of urgency. The authorities responsible for urban planning should devote part of the municipal budget to the creation of green infrastructure in the peri-urban and rural parts of cities.

5. Conclusions

The present study conducted a comparative analysis of the GI of the cities of Bujumbura, Kinshasa, and Lubumbashi. The spatial structure indices revealed that Bujumbura and Kinshasa's GI is characterized by the suppression of patches, whereas Lubumbashi exhibits fragmentation. The mean area of the GI slightly increased in Bujumbura and Kinshasa but decreased significantly in Lubumbashi. Dominance values rose in Bujumbura, while they declined in Kinshasa and Lubumbashi. The stability index indicated weak dynamics in Kinshasa, contrasting with more active changes in Bujumbura and Lubumbashi. The aggregation index suggested a decline in patch continuity in Bujumbura, while Kinshasa and Lubumbashi showed increased patch aggregation. The fractal dimension index highlighted the human impact on the GI of all three cities. These findings substantiate our hypothesis that the GI of these three cities exhibits a distinctive dynamic. However, the NDVI values showed a sawtooth evolution of tall vegetation in Bujumbura, with a gradual decrease in Kinshasa and Lubumbashi. The findings emphasize the need for urban planning to ensure adequate, multifunctional, and interconnected GI, which is vital not only for urban biodiversity but also for the sustainability of ecosystem services. Greening cities is essential for their social, environmental, and economic benefits, making the preservation and enhancement of natural capital imperative.

Author Contributions: Conceptualization, H.K. and J.B.; methodology, H.K.; N.C.C.; H.K.M.; W.S.; K.R.S.; Y.U.S. and J.B.; software, H.K.; D.M.; N.C.C.; H.K.M. and W.S.; validation, H.K.; Y.U.S.; K.R.S. and J.B.; formal analysis, H.K.; W.S.; N.C.C. and H.K.M.; investigation, H.K.; H.K.M.; N.C.C. and K.R.S.; resources, H.K.; H.K.M.; N.C.C. and K.R.S.; writing—original draft preparation, H.K.; writing—review and editing, H.K.; N.C.C.; D.M.; L.M.P.; W.S.; K.R.S.; Y.U.S.; T.M. and J.B.; visualization, H.K. and J.B.; supervision, H.K.; Y.U.S.; K.R.S.; T.M. and J.B.; Project administration, H.K.; T.M. and J.B.; funding acquisition, J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Académie de Recherche et d'Enseignement Supérieur-Commission de la Coopération au Développement (ARES-CCD, PSRCI-UB programme, UB R 4).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: We would like to thank all the co-authors for providing the information that made this comparative study possible.

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

References

1. OECD/CSAO. *Cahiers de l'Afrique de l'Ouest: Dynamiques de l'Urbanisation Africaine 2020: Africapolis, Une Nouvelle Géographie Urbaine*; OECD: Paris, France, 2020; ISBN 9789264349025.
2. Angel, S.; Parent, J.; Civco, D.L.; Blei, A.; Potere, D. The Dimensions of Global Urban Expansion: Estimates and Projections for All Countries, 2000-2050. *Prog. Plann.* **2011**, *75*, 53–107. [CrossRef]
3. Sanyal, S. *The End of Population Growth*; Deutsche Bank AG: Hong Kong, China, 2011; pp. 1–13.
4. Vermeiren, K.; Van Rompaey, A.; Loopmans, M.; Serwajja, E.; Mukwaya, P. Urban Growth of Kampala, Uganda: Pattern Analysis and Scenario Development. *Landsc. Urban Plan.* **2012**, *106*, 199–206. [CrossRef]
5. Vivet, J. Déplacés de Guerre et Dynamiques Territoriales Postconflit Au Mozambique. *Hérodote* **2015**, *158*, 160. [CrossRef]
6. Lavergne, M. De La Cuvette Du Haut-Nil Aux Faubourgs de Khartoum: Les Déplacés Du Sud-Soudan. Déplacés et Réfugiés, La Mobilité Sous La Contrainte. *Ed. l'IRD* **1999**, 109–136.
7. Schäffler, A.; Swilling, M. Valuing Green Infrastructure in an Urban Environment under Pressure - The Johannesburg Case. *Ecol. Econ.* **2013**, *86*, 246–257. [CrossRef]
8. Bogaert, J.; Vranken, I.; Andre, M. Biocultural Landscapes. *Biocultural Landsc.* **2014**. [CrossRef]
9. Madureira, H.; Cormier, L. La Complexité de l' Application Du Concept d' Infrastructure Verte à l' Échelle Locale: Exemples de Paris et Porto. In *Urbanités Biodiversité. Entre Villes Fertiles Campagnes Urbaines, Quelle Place Pour La Biodiversité?* HAL Open Science: Lyon, France, 2017.
10. Zhou, X.; Wanghe, K.; Jiang, H.; Ahmad, S.; Zhang, D. Construction of Green Infrastructure Networks Based on the Temporal and Spatial Variation Characteristics of Multiple Ecosystem Services in a City on the Tibetan Plateau: A Case Study in Xining, China. *Ecol. Indic.* **2024**, *163*, 112139. [CrossRef]
11. Osseni, A.A.; Mouhamadou, T.; Tohoain, B.A.C.; Sinsin, B. SIG et Gestion Des Espaces Verts Dans La Ville de Porto-Novo Au Benin. *Tropicultura* **2015**, *332*, 146–156.
12. du Toit, M.J.; Cilliers, S.S.; Dallimer, M.; Goddard, M.; Guenat, S.; Cornelius, S.F. Urban Green Infrastructure and Ecosystem Services in Sub-Saharan Africa. *Landsc. Urban Plan.* **2018**, *180*, 249–261. [CrossRef]
13. Gashu, K.; Egziabher, T.G. Spatiotemporal Trends of Urban Land Use / Land Cover and Green Infrastructure Change in Two Ethiopian Cities: Bahir Dar and Hawassa. *Environ. Syst. Res.* **2018**. [CrossRef]
14. Fomba, M.; Osunde, Z.D.; Traoré, S.S.; Okhimamhe, A.; Kleemann, J.; Fürst, C. Urban Green Spaces in Bamako and Sikasso, Mali_ Land Use Changes and Perceptions. *Land* **2024**, *13*, 59. [CrossRef]
15. Useni, Y.S.; Malaisse, F.; Yona, J.M.; Mwamba, T.M.; Bogaert, J. Diversity, Use and Management of Household-Located Fruit Trees in Two Rapidly Developing Towns in Southeastern D.R. Congo. *Urban For. Urban Green.* **2021**, *63*, 127220. [CrossRef]
16. Turner, S.C.; Turner, R.N. Capital Cities: A Special Case in Urban Development. *Ann. Reg. Sci.* **2011**, *46*, 19–35. [CrossRef]
17. Washbourne, C. Environmental Policy Narratives and Urban Green Infrastructure: Reflections from Five Major Cities in South Africa and the UK. *Environ. Sci. Pol.* **2022**, *129*, 96–106. [CrossRef]
18. Delgado-Capel, M.; Cariñanos, P. Towards a Standard Framework to Identify Green Infrastructure Key Elements in Dense Mediterranean Cities. *Forests* **2020**, *11*, 1246. [CrossRef]
19. Turner, M.G. Landscape Ecology: The Effect of Pattern on Process. *Annu. Rev. Ecol. Syst.* **1989**, *20*, 171–197. [CrossRef]
20. Messina Ndzomo, J.P.; Sambieni, K.R.; Mbevo Fendoung, P.; Mate Mweru, J.P.; Bogaert, J.; Halleux, J.M. La Croissance De L'Urbanisation Morphologique À Kinshasa Entre 1979 Et 2015: Analyse Densimétrique Et De La Fragmentation Du Bâti. *BSGLg* **2019**, *73*, 85–103. [CrossRef]
21. Bigirimana, J. Urban Plant Diversity Patterns, Processes and Conservation Value in Sub-Saharan Africa: Case of Bujumbura in Burundi. Ph.D. Thesis, Université libre de Bruxelles, Brussels, Belgium, 2012.
22. Mavunda, C.A.; Kanda, M.; Folega, F.; Egbelou, V.; Bosela, B.; Drazo, N.A.; Yoka, J.; Dourma, M. Dynamique Spatio-Temporelle Des Changements d ' Occupation Du Sol Sous Incidence Anthropique Dans La Ville de Kinshasa (RDC) de 2001 à 2021. *Geo-Eco-Trop* **2022**, *46*, 137–148.
23. Useni, Y.S. Analyse Spatio-Temporelle Des Dynamiques d'anthropisation Paysagère Le Long Du Gradient Urbain-Rural de La Ville de Lubumbashi (Haut-Katanga, République Démocratique Du Congo). Ph.D. Thesis, Université de Lubumbashi République Dé-mocratique du Congo, Lubumbashi, Democratic Republic of the Congo, 2017.
24. Maréchal, J.; Useni, S.Y.; Bogaert, J.; Munyemba, K.F.; Mahy, G. La Perception par des Experts Locaux des Espaces Verts et de Leurs Services Écosystémiques Dans Une Ville Tropicale En Expansion: Le Cas de Lubumbashi. In *Anthropisation des Paysages Katangais*; Bogaert, J., Colinet, G., Mahy, G., Eds.; Presse Universitaire de Liège: Gembloux, Belgium, 2018; pp. 59–69.
25. Mashagiro, G.Q.; Mujinya, B.B.; Colinet, G.; Mahy, G. Vegetation Degradation Alters Soil Physicochemical Properties and Potentially Affects Ecosystem Services in Green Spaces of a Tropical Megacity (Lubumbashi, DR Congo). *Geoderma Reg.* **2024**, *37*. [CrossRef]
26. Useni Sikuzani, Y.; Mpibwe Kalenga, A.; Yona Mleci, J.; N'Tambwe Nghonda, D.; Malaisse, F.; Bogaert, J. Assessment of Street Tree Diversity, Structure and Protection in Planned and Unplanned Neighborhoods of Lubumbashi City (DR Congo). *Sustainability* **2022**, *14*, 3830. [CrossRef]
27. Useni Sikuzani, Y.; Boisson, S.; Cabala Kaleba, S.; Nkuku Khonde, C.; Malaisse, F.; Halleux, J.-M.; Bogaert, J.; Munyemba Kankumbi, F. Dynamique de l' Occupation Du Sol Autour Des Sites Miniers: Analyse à Long Terme de La Structure Spatiale à Lubumbashi. *Biotechnol. Agron. Soc. Env.* **2019**, *24*, 14–27.

28. Biona, B. Classification Des Series Temporelles Landsat-8 Pour La Cartographie Du Gradient De Vegetation Dans Le Nord De La Republique Du Congo. *Sci. Tech.* **2017**, *16*, 1815–4433.
29. Useni, Y.S.; Mukenza, M.; Mpanza, M.M.; Malaisse, F.; Bogaert, J. Investigating of Spatial Urban Growth Pattern and Associ-ated Landscape Dynamics in Congolese Mining Cities Bordering Zambia from 1990 to 2023. *Resources* **2024**, *13*, 107. [CrossRef]
30. Salmon, M.; Ozer, A.; Pissart, A. Les Images Satellitaires Prises En Période de Sécheresse, Outil Utile Pour La Cartographie Géologique de La Belgique. *Bull. la Société Géographique Liège* **2007**, *49*, 67–74.
31. Soucy-Gonthier, N.; Marceau, D.; Delage, M.; Cogliastro, A.; Domon, G.; Bouchard, A. *Détection de l'évolution des Superficies Forestières en Montérégie Entre Juin 1999 et Août 2002 à Partir d'images Satellitaires LandSat-TM*; Université de Montréal: Montreal, QC, Canada, 2003.
32. Zurqani, H.A.; Post, C.J.; Mikhailova, E.A.; Schlautman, M.A.; Sharp, J.L. Geospatial Analysis of Land Use Change in the Savannah River Basin Using Google Earth Engine. *Int. J. Appl. Earth Obs. Geoinf.* **2018**, *69*, 175–185. [CrossRef]
33. Zhu, Z.; Woodcock, C.E. Object-Based Cloud and Cloud Shadow Detection in Landsat Imagery. *Remote Sens. Environ.* **2012**, *118*, 83–94. [CrossRef]
34. Bonn, F.; Rochon, G. *Précis de Télédétection. Principes et Méthodes*; Presses de l'Université du Québec: Québec, QC, Canada, 1992.
35. Floreano, I.X.; de Moraes, L.A.F. Land Use/Land Cover (LULC) Analysis (2009–2019) with Google Earth Engine and 2030 Prediction Using Markov-CA in the Rondônia State, Brazil. *Environ. Monit. Assess.* **2021**, *193*, 239. [CrossRef] [PubMed]
36. Girard, M.C.; Girard, C.M. *Traitement Des Données de Télédétection*, 2nd ed.; Dunod: Paris, France, 2010.
37. Mama, V.J.; Oloukoi, J. Évaluation de La Précision Des Traitements Analogiques Des Images Satellitaires Dans l'étude de La Dynamique de l'occupation Du Sol. *Télédétection* **2003**, *3*, 429–441.
38. Bogaert, J.; Vranken, I.; Andre, M. Anthropogenic Effects in Landscapes: Historical Context and Spatial Pattern. In *Biocultural Landscapes: Diversity, Functions and Values*; Springer: Berlin, Germany, 2014; pp. 89–112. [CrossRef]
39. Davidson, C. Issues in Measuring Landscape Fragmentation. *Wildl. Soc. Bull.* **1998**, 32–37.
40. He, H.S.; DeZonia, B.E.; Mladenoff, D.J. An Aggregation Index (AI) to Quantify Spatial Patterns of Landscapes. *Landsc. Ecol.* **2000**, *15*, 591–601. [CrossRef]
41. Hesselbarth, M.H.K.; Scianini, M.; With, K.A.; Wiegand, K.; Nowosad, J. Landscaperemetrics: An Open-Source R Tool to Calculae Landscape Ma-trics. *Ecography* **2019**, *42*, 1648–1657. [CrossRef]
42. Diallo, H.; Bamba, I.; Barima, Y.S.S.; Visser, M.; Ballo, A.; Mama, A.; Vranken, I.; Maiga, M.; Bogaert, J. Effets Combinés Du Climat et Des Pressions Anthropiques Sur La Dynamique Évolutive de La Dégradation d'une Aire Protégée Du Mali (La Réserve de Fi-na, Boucle Du Baoulé). *Sci. Chang. Plan.* **2011**, *22*, 97–107.
43. Krummel, J.R.; Gardner, R.H.; Sugihara, G.; O'neill, R.V.; Coleman, P.R. Landscape Patterns in a Disturbed Environment. *Oikos* **1987**, 321–324. [CrossRef]
44. Bogaert, J.; Ceulemans, R.; Salvador-Van Eysenrode, D. Decision Tree Algorithm for Detection of Spatial Processes in Landscape Transformation. *Environ. Manag.* **2004**, *33*, 62–73. [CrossRef]
45. de Haulleville, T.; Rakotondrasoa, O.L.; Rakoto Ratsimba, H.; Bastin, J.F.; Brostaux, Y.; Verheggen, F.J.; Rajoelison, G.L.; Malaisse, F.; Poncelet, M.; Haubruge, É.; et al. Fourteen Years of Anthropization Dynamics in the Uapaca Bojeri Baill. Forest of Madagascar. *Landsc. Ecol. Eng.* **2018**, *14*, 135–146. [CrossRef]
46. Tente, O.; Oloukoi, J.; Toko, I.; Tente, O.; Oloukoi, J.; Toko, I. Dynamique Spatiale et Structure Du Paysage Dans La Commune de Zè, Bénin. In *OSFACO Conference: Satellite Images for Sustainable Land Management in Africa*; CBFP: Washington, DC, USA, 2019.
47. Razagui, A.; Bachari, N.E.I. Spatio-Temporal Analysis of NDVI Vegetation Index Calculated from NOAA and MSG Satellite Images. *J. Renew. Energ.* **2014**, *17*, 497–506.
48. Vani, V.; Mandla, V.R. Comparative Study of NDVI and SAVI Vegetation Indices in Anantapur District Semi-Arid Areas. *Int. J. Civ. Eng. Technol.* **2017**, *8*, 559–566.
49. Huete, A.; Didan, K.; Van Leeuwen, W.; Miura, T.; Glenn, E. *Land Remote Sensing and Global Environmental Change: NASA's Earth Observing System and the Science of ASTER and MODIS*; Springer: Berlin/Heidelberg, Germany, 2011; p. 894. [CrossRef]
50. Meneses-Tovar, C.L. L'indice Différentiel Normalisé de Végétation Comme Indicateur de La Dégradation. *Unasylva* **2011**, *62*, 39–46.
51. Landis, J.R.; Koch, G.G. The Measurement of Observer Agreement for Categorical Data Data for Categorical of Observer Agreement The Measurement. *Biometrics* **1977**, *33*, 159–174. [CrossRef]
52. Foody, G.M. Assessing the Accuracy of Land Cover Change with Imperfect Ground Rerefence Data. *Remote Sens. Envirn.* **2010**, *144*, 2271–2285. [CrossRef]
53. Hesselbarth, M.H.K.; Nowosad, J.; Signer, J.; Graham, L.J. Open-Source Tools in R for Landscape Ecology. *Curr. Landsc. Ecol. Rep.* **2021**, *6*, 97–111. [CrossRef]
54. Kayiranga, A.; Kurban, A.; Ndayisaba, F.; Nahayo, L.; Karamage, F.; Ablekim, A.; Li, H.; Ilniyaz, O. Monitoring Forest Cover Change and Fragmentation Using Remote Sensing and Landscape Metrics in Nyungwe-Kibira Park. *J. Geosci. Environ. Prot.* **2016**, *4*, 13–33. [CrossRef]
55. Simwanda, M.; Ranagalage, M.; Estoque, R.C.; Murayama, Y. Spatial Analysis of Surface Urban Heat Islands in Four Rapidly Growing African Cities. *Remote Sens.* **2019**, *11*, 1645. [CrossRef]
56. Forman, R.T. T Some General Principles of Landscape and Regional Ecology. *Landsc. Ecol.* **1995**, *10*, 133–142. [CrossRef]
57. Burel, F.; Baudry, J. *Ecologie Du Paysage. Concepts, Méthodes et Applications*; Tec & Doc.: Paris, France, 2003.

58. Haila, Y. A Conceptual Genealogy of Fragmentation Research: From Island Biogeography to Landscape Ecology. *Ecol. Appl.* **2002**, *12*, 321–334. [CrossRef]
59. Mouhamadou, I.; Imorou, I.; Mèdaho, A.; Sinsin, B. Perceptions Locales Des Déterminants de La Fragmentation Des Îlots de Forêts Denses Dans La Région Des Monts Kouffé Au Bénin. *J. Appl. Biosci.* **2013**, *66*, 5049. [CrossRef]
60. Ducrot, D. *Méthodes d'analyses et d'interprétation d'images de Télédétection Multisource. Extraction de Caractéristiques Du Paysage*; INP: Toulouse, France, 2005.
61. Mouhamadou, I.T.; Touré, F.; Imorou, I.T.; Sinsin, B. Indices de Structures Spatiales Des Îlots de Forêts Denses Dans La Région Des Monts Kouffé. *VertigO* **2012**, *12*, 1–17. [CrossRef]
62. Delcros, P. *Ecologie Du Paysage et Dynamique Végétale Post-Culturale*; CEMAGREF: Fresnes, France, 1994; p. 13. ISBN 2853623823.
63. Bogaert, J.; Rousseau, R.; Van Hecke, P.; Impens, I. Alternative Area-Perimeter Ratios for Measurement of 2D Shape Compactness of Habitats. *Appl. Math. Comput.* **2000**, *111*, 71–85. [CrossRef]
64. Dupin, L.; Nkono, C.; Burlet, C.; Muhashi, F.; Vanbrabant, Y. Land Cover Fragmentation Using Multi-Temporal Remote Sensing on Major Mine Sites in Southern Katanga (Democratic Republic of Congo). *Adv. Remote Sens.* **2013**, *02*, 127–139. [CrossRef]
65. Kabuanga, J.M.; Adipalina Guguya, B.; Ngenda Okito, E.; Maestripieri, N.; Saqalli, M.; Rossi, V.; Iyongo Waya Mongo, L. Suivi de l'anthropisation Du Paysage Dans La Région Forestière de Babagulu, République Démocratique Du Congo. *VertigO* **2020**, *20*, 1–27. [CrossRef]
66. Romero-Sanchez, M.E.; Ponce-Hernandez, R. Assessing and Monitoring Forest Degradation in a Deciduous Tropical Forest in Mexico via Remote Sensing Indicators. *Forests* **2017**, *8*, 302. [CrossRef]
67. Diello, P.; Mahe, G.; Paturel, J.-E.; Dezetter, A.; Delclaux, F.; Servat, E.; Ouattara, F. Relations Indices de Végétation–Pluie Au Burkina Faso: Cas Du Bassin Versant Du Nakambé. *Hydrol. Sci. J.* **2005**, *50*, 221. [CrossRef]
68. Hao, F.; Zhang, X.; Ouyang, W.; Skidmore, A.K.; Toxopeus, A.G. Vegetation NDVI Linked to Temperature and Precipitation in the Upper Catchments of Yellow River. *Environ. Model. Assess.* **2012**, *17*, 389–398. [CrossRef]
69. Bangirinama, F.; Nzitwanayo, B.; Hakizimana, P. Utilisation Du Charbon de Bois Comme Principale Source d'énergie de La Population Urbaine: Un Sérieux Problème Pour La Conservation Du Couvert Forestier Au Burundi. *Bois Forets des Trop.* **2016**, *8*, 45–53. [CrossRef]
70. Bolund, P.; Hunhammar, S. Ecosystem Services in Urban Areas. *Ecol. Econ.* **1999**, *29*, 293–301. [CrossRef]
71. Lotfi, M.; Christiane, W.; Pietro Francesca, D.; Wissal, S. Les Services Écosystémiques Urbains, Vers Une Multifonctionnalité Des Espaces Verts Publics: Revue de Littérature. *Environ. Urbain/Urban Environ.* **2017**, *11*.
72. Attoumani, A.; Victor, R.; Randriamampandry, C. La Croissance de La Ville d'Antananarivo et Ses Conséquences. *Madamines* **2019**, *1*, 1–25.
73. Kong, F.; Nakagoshi, N. Spatial-Temporal Gradient Analysis of Urban Green Spaces in Jinan, China. *Landsc. Urb. Plan.* **2006**, *78*, 147–164. [CrossRef]
74. Mcdonald, R.I.; Forman, R.T.T.; Kareiva, P. Open Space Loss and Land Inequality in United States' Cities, 1990–2000. *PLoS ONE* **2010**, *5*, e9509. [CrossRef]
75. Toyi, O. Politiques Publiques Urbaines de l'Habitat Dans la Ville de Bujumbura de 1962 a 2009. Ph.D. Thesis, Université de Pau et des Pays de l'Adour, Pau, France, 2012.
76. Mangenda, H.H.; Tshibuabua, F.M.; Bokako, C.E.; Dihoka, F.; Kandala, D. Urban Growth and Environmental Degradation in the Municipality of Kalamu, Kinshasa. *Hal* **2023**. Available online: https://hal.science/hal-04151946 (accessed on 22 July 2024).
77. Ujoh, F.; Dlama, K.I.; Oluseyi, I.O. Urban Expansion and Vegetal Cover Loss in and around Nigeria' s Federal Capital City. *J. Ecol. Nat. Environ.* **2011**, *3*, 1–10.
78. Koumoi, Z.; Alassane, A.; Djangbedja, M.; Boukpessi, T.; Kouya, A.-E. Dynamique Spatio-Temporelle de l'occupation Du Sol Dans Le Centre-Togo. *AHOHO-Rev. Géographie LARDYMES* **2013**, *7*, 163–172.
79. Tungi, J.; Luzolo, T.; Ngembo, E.N.; Masivi, C.L.; Landu, E.L.; Kibwila, M.N. Pression Exercée Par Les Entreprises Pâtissières Artisanales et Nganda Ntaba Sur La Végétation Arborée Urbaine et Périurbaine à Kinshasa En République Démocratique Du Congo. *Int. J. Innov. Sci. Res.* **2022**, *62*, 25–39.
80. Twite, G.; Balume, S. *Utilisation Énergétique à l ' Échelle Urbaine En République Démocratique Du Congo: État de Lieux, Défis et Perspectives Energy Use at the Urban Scale in the Democratic Republic of Congo: State of Affairs, Challenges and Perspectives*; ISTE Ltd.: London, UK, 2000; pp. 1–19.
81. Arnaud, Y.P.; Célestin, A.Y. Problematique de la Gestion Durable de la Foret Periurbaine de l'Anguededou (Abidjan, Cote D'Ivoire). *Rev. Sci. Tchad* **2016**, *36*, 40–50.
82. Kabisch, N. Ecosystem Service Implementation and Governance Challenges in Urban Green Space Planning-The Case of Berlin, Germany. *Land Use Policy* **2015**, *42*, 557–567. [CrossRef]
83. Larson, K.L.; Nelson, K.C.; Samples, S.R.; Hall, S.J.; Bettez, N.; Cavender-Bares, J.; Groffman, P.M.; Grove, M.; Heffernan, J.B.; Hobbie, S.E.; et al. Ecosystem Services in Managing Residential Landscapes: Priorities, Value Dimensions, and Cross-Regional Patterns. *Urban Ecosyst.* **2016**, *19*, 95–113. [CrossRef]

84. Cohen, B. Urban Growth in Developing Countries: A Review of Current Trends and a Caution Regarding Existing Forecasts. *World Dev.* **2004**, *32*, 23–51. [CrossRef]
85. Angelone, S.; Holderegger, R. Population Genetics Suggests Effectiveness of Habitat Connectivity Measures for the European Tree Frog in Switzerland. *J. Appl. Ecol.* **2009**, *46*, 879–887. [CrossRef]

land

Article

Geospatial Prioritization of Terrains for "Greening" Urban Infrastructure

Bilyana Borisova , Lidiya Semerdzhieva *, Stelian Dimitrov , Stoyan Valchev, Martin Iliev and Kristian Georgiev

Faculty of Geology and Geography, Sofia University St. Kliment Ohridski, 1504 Sofia, Bulgaria; billiana@gea.uni-sofia.bg (B.B.); stelian@gea.uni-sofia.bg (S.D.); stojanv@uni-sofia.bg (S.V.); martin@gea.uni-sofia.bg (M.I.); kristiyang@uni-sofia.bg (K.G.)
* Correspondence: l.nikolaeva@gea.uni-sofia.bg

Abstract: This study aims to scientifically justify the identification of suitable urban properties for urban green infrastructure (UGI) interventions to optimize its natural regulating functions for long-term pollution mitigation and secondary dust reduction. This study adheres to the perception that planning urban transformations to improve ambient air quality (AQ) requires a thorough understanding of urban structural heterogeneity and its interrelationship with the local microclimate. We apply an approach in which UGI and its potential multifunctionality are explored as a structural–functional element of urban local climatic zones. The same (100 × 100 m) spatial framework is used to develop place-based adapted solutions for intervention in UGI. A complex geospatial analysis of Burgas City, the second largest city (by area) in Bulgaria, was conducted by integrating 12 indicators to reveal the spatial disbalance of AQ regulation' demand and UGI's potential to supply ecosystem services. A total of 174 municipally owned properties have been identified, of which 79 are of priority importance, including for transport landscaping, inner-quarter spaces, and social infrastructure. Indicators of population density and location of social facilities were applied with the highest weight in the process of prioritizing sites. The study relies on public data and information from the integrated city platform of Burgas, in cooperation with the city's government. The results have been discussed with stakeholders and implemented by the Municipality of Burgas in immediate greening measures in support of an ongoing program for Burgas Municipality AQ improvement.

Keywords: air pollution; urban ecosystem services; green infrastructure; local climate zones; sustainable urban planning; Burgas city

Citation: Borisova, B.; Semerdzhieva, L.; Dimitrov, S.; Valchev, S.; Iliev, M.; Georgiev, K. Geospatial Prioritization of Terrains for "Greening" Urban Infrastructure. *Land* **2024**, *13*, 1487. https://doi.org/10.3390/land13091487

Academic Editors: Luca Battisti, Fabrizio Aimar and Federico Cuomo

Received: 15 August 2024
Revised: 4 September 2024
Accepted: 6 September 2024
Published: 13 September 2024

1. Introduction

The growth of urban populations [1] and urban sprawl [2] presents us with some of the most serious challenges in maintaining our living environment and health. The degradation of natural ecosystems that accompanies urban densification poses a growing threat to the long-term provision of many of the ecosystem services that are vital to urban populations [3] and permanently limits the resilience of cities to climate change [4].

The concept of ecosystem services (ESs) has been attracting growing interest in the scientific milieu and in the arena of policymaking over the last 20 years [5,6]. ESs are related to operational concepts such as Green Infrastructure (GI), Nature-based Solutions (NBSs), and Ecosystem-based Adaptation (EbA). The impact of urban parks on human well-being and thermal comfort has been investigated by a considerable number of studies for diverse climatic conditions [7–10]. Managing the desired benefits of urban green spaces has been the subject of in-depth discussions in urban management and planning policies [11–14], where interventions in NBSs find a logical place [15]. NBSs are most clearly oriented towards providing solutions to complex challenges, in terms of urban structure and functionality, and can be seen as a sufficiently flexible approach to urban planning, in building on approaches to urban greening [16]. However, the latter requires a proper understanding of urban challenges in their local context to find an adequate response by stimulating the provision of ecosystem services [17,18]. Research in this regard offers an expanding interdisciplinarity and adheres to a systems perspective that approaches urban sustainability as a complex phenomenon [14].

Urban green infrastructure (UGI) is part of urban morphology and has an important structuring significance for the development of urban spaces in terms of the desired heterogeneity of the urban environment. This is explained by the main regulating and supporting ecosystem functions and benefits of UGI in providing a favorable quality of living environment for people. However, research shows that the relationship between green spaces and ecosystem services provided is not straightforward and is dependent on urban typology [19–21]. In their comparative analysis of sets of urban typologies and associated ecosystem service packages in temperate and tropical climate cities, Adrienne Grêt-Regamey et al. 2020 [3] find that the supply of urban ESs does not increase linearly with greenspace coverage, but is strongly dependent on urban form. In built-up neighborhoods, the proportion of trees in the total green cover is essential for maintaining regulating ESs, but in terms of microclimate, this regulation depends on the size of the built-up area. The authors emphasize that medium-height open neighborhoods synergistically support the provision of regulatory services, including microclimate regulation and air pollution control. Research by Balzan et al. 2021 [22] in the ecological conditions of a Mediterranean city shows that the capacity of ESs is highest in the urban periphery and lowest in dense urban cores. Public gardens have low ecosystem service regulation capacity, in contrast to private gardens and urban trees, which have the highest ecosystem service regulation capacity per unit area. UGI is an important tool for cities to adapt to climate change, but there is still a lack of knowledge about the optimal planting design for urban spaces and its impact on outdoor thermal comfort [10]. With the advent of new and increasingly precise and accessible geospatial technologies, new opportunities are opening up for UGI displacements based on their integrated use, and this is one of the main objectives of the present study. There is an obvious lack of more practical, geodata-driven knowledge in this field. Another important point that is addressed in this work relates to the use of already established approaches to study key aspects of the urban environment, as in the case of LCZs, which are used in urban climatology and also in the present UGI study, in accordance with the principles of spatial autocorrelation. We see here a strong potential for the application of a scientific approach in which UGI and its potential multifunctionality are explored as a structural-functional element of urban local climatic zones. They are a well-established approach in the analysis of urban morphology-urban microclimate causal relationships and, in our view, can provide a successful spatial framework for developing a place-based adapted strategy for intervention in UGI.

The construction and purposeful maintenance of green spaces in Bulgarian cities have good traditions, resulting from the European cultural influences in park art from the beginning of the 20th century in architecture and urban planning (Sofia, Ruse, Plovdiv, Varna, Burgas). Political decisions in the planning and construction of urban spaces, distinctive for Eastern Europe in the mid and late twentieth century, directly affect the type and condition of green spaces as part of the urban structure. These include representative central city parks, preserved natural tree vegetation in the old parts of the cities and cemetery parks, wide landscaped and mostly grassy expanses in new residential districts, and often isolated suburban green areas which are usually territorially linked to nearby protected natural or cultural sites. The serious political changes of the late twentieth century generated significant changes in the functional specialization of cities, and for some of them led to uncontrolled sprawl (mostly regional cities), greatly complicating their urban structure. Losses of green spaces, changes in their condition, or alterations in their use have been documented.

European policies in the protection and utilization of ecosystem functions through the construction and maintenance of green infrastructure are reflected in Bulgarian political documents [23]. However, the development of a concept for GI in local conditions, and especially a long-term vision for its targeted maintenance and conservation with the motivated cooperation of the public, takes time. The reason for this is primarily rooted in the need to establish an urban planning concept that is adequate to contemporary urban needs and that plans and integrates the functions of green spaces as an integral part of the urban system and a form of infrastructure. However, this is a difficult process whose constraints are rooted in the management conditions on heterogeneous ownership of urban properties, demographic pressures (in the direction of population influx or outflow) stimulating new construction and the expansion of the service sector, or vice versa with issues relating to abandoned buildings and disturbed land. Unfortunately, the fact that the topic of green spaces and their functions is successfully used for political purposes, but the actual construction of green spaces is financed by separate municipal, NGO, or private projects, not always temporally or territorially coordinated, is also relevant here.

For smaller settlements (fewer than 50,000 inhabitants) there is a very general and wishful style of urban policies in managing green spaces. Still, the financial resources are sufficient mainly for the seasonal landscaping of urban gardens in widely publicly accessible urban squares and main pedestrian streets. The Association of Municipalities in Bulgaria has recognized a practical manual for UGI [24], but we will have to see how effective its implementation is in the future.

The main challenge in the implementation of European and national policies (top-down) related to urban greening on a local scale, in our view, is the need to apply an individual approach (bottom-up) in the construction and maintenance of green infrastructure concerning the local geography, the inherent urban structure (settlement development in a historical and geographical context), the demographic profile, and the leading administrative, economic, and cultural functions of the city. However, this depends on the local institutional capacity in solving the current problems of the city, as derivatives of its complexity. On this basis, we assume that a good spatial analysis of the urban morphology and the possibilities for its development given the active variables—population, economy, services, and consumption—enables the construction of green infrastructure, sufficiently flexibly inscribed in the urban structure so that it fulfills its ecological functions to the full. The research of Croeser et al., 2021 [25] draws attention to the potential of multi-criteria decision analysis (MCDA), including the importance of user feedback for the co-creation of knowledge and the selection of adequate solutions to address various urban challenges.

The focus of the present study is a persistent problem for large Bulgarian cities (over 200,000 people): their high vulnerability to dust pollution. This is derived to a high degree from inherited problems of urban structures in the course of their territorial expansion, the change of priority functions under the influence of political changes, demographic variables, and last but not least, geographical conditions. The procedure "Green infrastructure in an urban environment" in the direction "Air" under Operational Program "Environment" 2021–2027 of Bulgaria, financed through the European Structural Funds, supports the greening of urbanized territories, including innovative approaches (NBS). In this regard, municipalities affected by air quality (AQ) problems have the opportunity to receive funding for landscaping investments aimed at reducing secondary dust pollution and improving AQ.

The study presents comprehensive research results in Burgas, the second-largest urban area city in Bulgaria, with leading economic functions in South-Eastern Bulgaria. The main objective of the study is to develop and test a model for geospatial analysis of the urbanized area of Burgas to select locations where the construction of new or the renovation of existing green infrastructure elements can contribute sustainably to the reduction and mitigation of air pollution, and in particular secondary dust pollution. The study is based on the relationship between urban morphology, the green system, and ecosystem services for air quality regulation. The results support Burgas's urban planning and greening concepts.

This has been realized in active cooperation with the Municipality of Burgas: we have approached this with the understanding that the model must be understandable for the managers and able to undergo periodic discussion and optimization as a result of effective feedback from the interested parties. The study was carried out with the following pre-set requirements: (1) the study should interpret the relationship between GI and ESs in the context of Burgas' distinctive urban structural heterogeneity; (2) the study should use local data (information maintained and integrated by the local authority for city management purposes, and potentially updatable through regular monitoring programs); and (3) the results should have a long-term effect on the reduction in PM with successful synergy with other regulating ecosystem services necessary for the city, such as cooling effects, climate comfort, and habitat functions. The desired result is a sustainable provision of ESs for PM reduction in support of the activities laid down in the current "Program for improving the air quality of the municipality of Burgas for 2021–2027" [26].

2. Materials and Methods

Significant epidemiological studies in the scientific literature find that air pollution contributes to increased morbidity [27]. Air pollution, mainly caused by nitrogen dioxide (NO_2) and fine particulate matter with an aerodynamic diameter below 2.5 µm ($PM_{2.5}$), is today the leading environmental cause of death worldwide, causing over 3 million premature deaths per year, more than twice the number of deaths from road traffic accidents [1]. Green areas and their ecological functions contribute to ambient AQ by reducing and removing air pollutants, especially PM. This has been demonstrated in many studies in recent years, and interest in the topic has increased concerning the increased incidence of disease in urban populations in densely built settlements [28–31].

Ground-level concentrations of air pollutants in cities are a complex function of emissions, dispersion, and deposition of pollutants, and chemical processes in the surface air layer. These processes are largely influenced by the geospatial structure of the city. The conceptual framework of this study is based on several key assumptions related to the role of UGI. We assume that UGI will have the most significant impact on AQ by stimulating natural ventilation; changing the mean aerodynamic roughness (which has a direct impact on pollutant dispersion); absorbing pollutants from green surfaces (leaves, branches, tree bark); limiting the formation of secondary pollutants due to cooling effects. Based on these initial positions, the analysis of the UGI elements of the urban area of Burgas is analyzed as an integral structural part of the city morphology.

2.1. Study Area

Burgas City is a functional urbanized area center with major industrial, transport, and tourist functions in South-Eastern Bulgaria. Burgas is located on the coast of Burgas Bay on the southern Black Sea coast (17 m a.s.l.) and experiences a continental Mediterranean climate (Cfa). It is the second largest urbanized area (254 km^2) after the metropolitan city of Sofia, and hosts 4% of the country's urban population [32]. It is distinguished by an over-concentrated urban core developed around a port, with annexed settlements from the agricultural periphery that are now important residential districts. The urban structure is set among three coastal lakes and the Black Sea (the city is surrounded by the largest complex of seaside lakes in the country) [33] (Figure 1). Its territory is distinguished by a concentration of protected areas of national and European importance.

The Environment Executive Agency of Bulgaria defines the city of Burgas as a zone/territorial unit in which atmospheric air pollution with fine dust particles (PM10) exceeds the permissible number of exceedances (up to 35 days/year of the average day and night norms of 50 µg/m^3). For 2016–2020, exceedances of up to 116 days (2017) were registered here, with average values for 74 days/year [34]. Since 2013, the territory has been part of the Autonomous Region for the Assessment and Management of AAQ and is obliged to develop and implement targeted programs to reduce pollutant levels. Within the scope of the analyzed area, there are year-round conditions for the retention of pollutants in the surface air layer: high frequency of maximum temperatures above 30 °C during the summer months; absolute maximum temperatures for the period June–August of up to 40–42 °C;

and high atmospheric humidity but insufficient amount of annual average precipitation (between 470 and 600 mm). Cases with low wind speeds (up to 1.5 m/s) reach 20–24% in the period from March to July, while in the remaining months, they vary between 12–15% (Program for Improvement of Ambient Air Quality in the Municipality of Burgas) [26,35]. The configuration of the city does not allow good ground ventilation, which confirms the strong influence of the city's morphology and its economic activity on microclimatic conditions and AQ.

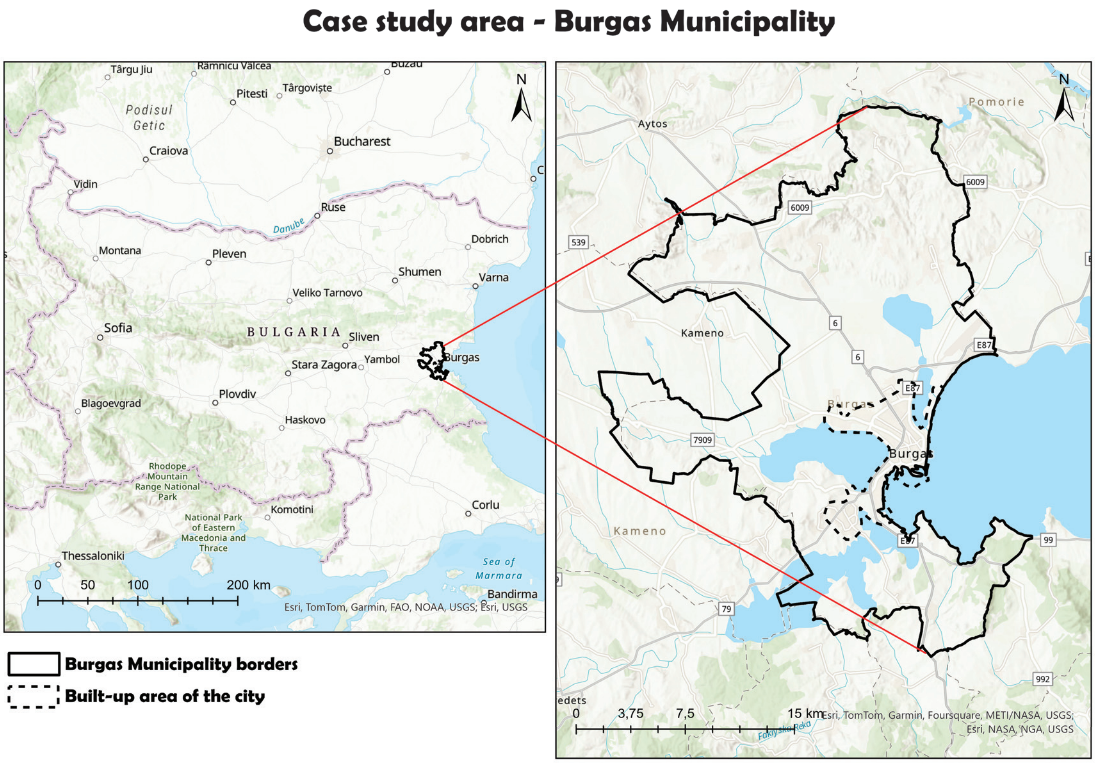

Figure 1. Study area—Burgas city and municipality.

Although the territory of the municipality is characterized by very good coverage of green spaces, the trends listed above make it imperative to consider expanding green spaces in urban environments to increase the cooling effect and aid in the sedimentation and reduction of air pollutants.

2.2. *Approaches and Methods for Geospatial Analysis of Urban Environment Related to Air Quality Improvement and Reduction in Secondary Dust Pollution*

This study proposes an approach for geospatial locational analysis of the urban morphostructure of the city of Burgas, aimed at a scientifically substantiated selection of sites/objects where the expansion or renovation of green areas can help reduce secondary dust pollution. The methodology integrates 12 indicators reflecting local conditions, including urban heterogeneity, locations with high concentrations of PM, local microclimatic conditions, conditions of the UGI, population, and social activities. The study is consistent with the principles of effectiveness and feasibility.

A methodological framework has been developed assuming the sequential implementation of the following work phases and activities (Figure 2):

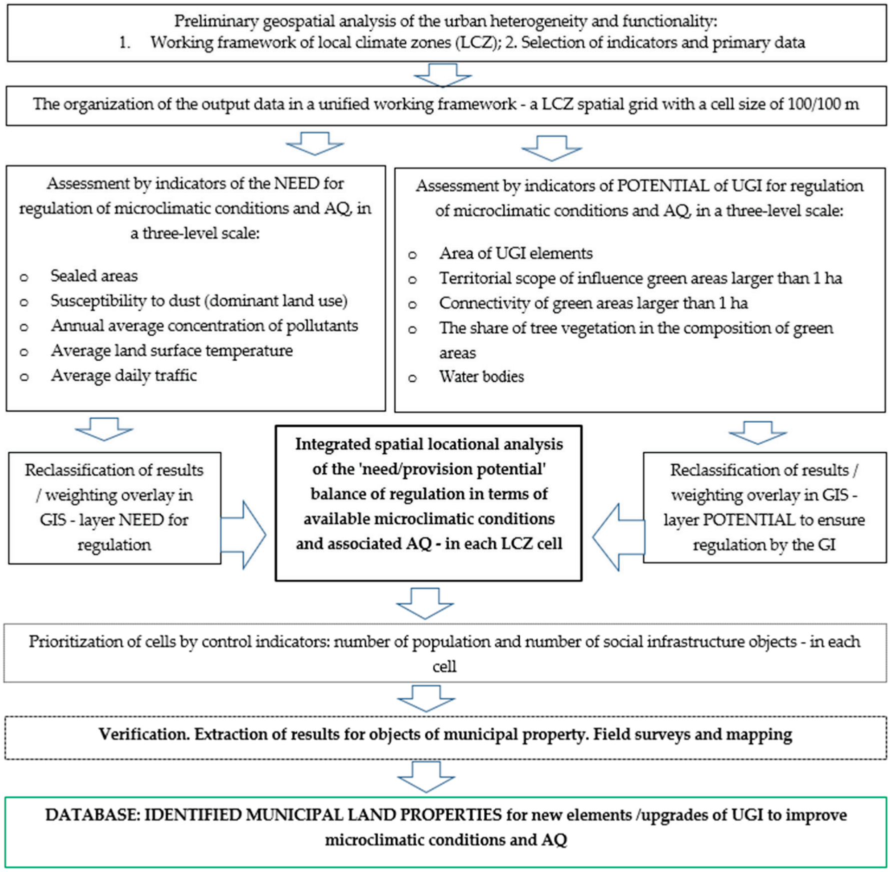

Figure 2. Methodological scheme.

Phase 1: Preliminary geospatial analysis of the urban spaces of Burgas to identify the main features of urban heterogeneity and functionality. This phase aims to define a basic working spatial unit (unified working framework) for carrying out spatial assessments and selecting indicators to reflect the influence of the urban environment on the AQ. For the preparation of a basic spatial unit, this study uses the concept of local climate zones, arguments for which are presented in item 2.3. A cell size of 100 × 100 m (area of 1 ha) is applied.

Phase 2: Unification. This phase includes the organization of the output working data according to the unified working framework defined in Phase 1 and the development of a scale consistent with the framework for measuring the selected indicators for territorial assessment: A three-level scale was chosen to evaluate a total of 12 indicators determined to be informative for the study.

Phase 3: Integrated spatial location analysis. This stage has three steps, as follows: 1. assessment by 5 indicators of the 'need' for regulation of microclimatic conditions and AQ, and assessment by 5 indicators of the 'potential' of UGI to ensure regulation of microclimatic conditions and AQ; 2. weighting overlay in a GIS by thematic grouping of the results of the evaluation of the indicated indicators for each cell of the LCZ; and 3. reclassification of the results and the identification of the 'need/provision potential' ratio for each LCZ cell—the aim being to identify cells in which there is a high need for AQ regulation, but a low available UGI potential.

Phase 4: Prioritization. This phase envisages prioritization of the cells with the most unfavorable 'need/provision potential' balance—a result of the previous phase. For this, the introduction of control indicators is foreseen: number of population and number of social infrastructure objects—for each LCZ cell. A three-level scale was used to rank the values of both control indicators.

Phase 5: Verification and discussion. This phase includes verification of the results through a detailed survey of the prioritized territories according to current photogrammetric data with and field visits; extraction of results for objects of municipal property; discussion of the results with the responsible persons in the municipality and other interested parties; and measurement of the areas within the properties for which greening measures are applicable.

Phase 6: Organization of the received information about the selected terrains/objects in a database: geolocation identifiers, reference to the property cadastre, the purpose of UGI concerning the type of permanent use of the terrain, and other attributive data obtained in the course of the research and thematic assessments.

A series of analytical operations were conducted in a GIS environment using ESRI's ArcGIS Pro software 3.2.0 to sequentially process the data.

2.3. Unified Working Framework for Spatial Assessments—Local Climate Zones

For the integrated locational analysis, this study applies the Climate Classification Methodology for Urban Areas [35], which allows the analysis of key features of the urban space in a system of cells with the meaning of "local climate zones" (LCZs). This decision is based on the following arguments: LCZs reflect urban morphology in specific spatial combinations of built area types and adjacent land cover [35]. Among the most important arguments is the potential of the LCZ to reflect the prerequisites for microclimatic conditions and corresponding AQ in the heterogeneous urban structure against the background of climate regimes common to the urban space of Burgas. In addition, LCZs determine important characteristics of urban climate (temperature regime, including the urban heat island effect (UHI), and surface air circulation), air quality, and dust and pollutant retention conditions [36,37]. LCZs could facilitate the discussion and mapping of spatial PM pollution [38]. LCZs are an effective framework for discussing urban sustainability and climate neutrality. The versatility, simplicity, and objectivity of the LCA framework make it a promising tool for a wide range of applications in the future, especially in the field of climate-smart urban planning and design [39]. LCZs are used as the main information unit in the definition of the typology of urban ecosystems in the Methodology for assessment and mapping of urban ecosystems and urban ecosystem services in Bulgaria [40]. On this basis, green urban infrastructure has been assessed as a provider of regulating Ess in terms of AQ.

The main stages of LCZ definition generally include the following research procedures: (1) grid size selection; (2) zone definition according to the classification scheme (Stewart and Oke, 2012), (3) visualization of the results; and (3) statistical characterization of the respective zones obtained by processing geostatistical data or data from field measurements [41].

2.4. Indicators

As a result of the preliminary analysis, a total of 12 indicators have been identified for participation in the integrated geospatial analysis (10 thematic and 2 control indicators). The selection is in line with the choice of the LCZ as the territorial unit for assessment. The final decision was made after a discussion with the Burgas Municipality regarding the provision of up-to-date data: the study uses data from the Smart Burgas integrated city information platform (https://smartburgas.eu/bg, (accessed on 13 August 2024)) [42], used by the local administration for the management of Burgas City and direct feedback to the residents of the city. These are data from regulatory local monitoring (air quality), including the functioning of urban infrastructure (such as 24 h car traffic); urban planning data (locations of social infrastructure sites), or data generated at the request of the municipality for urban planning purposes (photogrammetric surveys of the actual land cover of the city, including the extent of green areas); and data from open national data of the National Statistical Institute (population). A unified three-level scale has been developed to measure the indicators applied in the study (except for the "water bodies" indicator, where the actual presence of similar urban elements is taken into consideration). Each level of this scale assumes in the course of the assessment a corresponding weighting—high, medium, and low.

Indicators for the air quality assessment/demand to provide air quality regulation.

Five indicators were selected to reflect the relationship between urban heterogeneity and ambient air quality (Table 1). The sealing of natural surfaces in the process of urban development and sprawl with artificial or low permeability materials results in the permanent disruption of natural internal landscape processes such as water and air circulation, soil functions, biological nutrition, and bioproduction. The high concentration of sealing in Burgas and the compact urban structure (with a population density of 746 people/km^2) contribute to the retention of high concentrations of PM in ground air and resuspension of PM. The indicator of susceptibility to dust reflects the leading type of land use in the respective LCZ grid cell. Here, the assumption is made that according to the type of land use and the functioning of the respective territory (residential, industrial, transport, public services, sport and recreation, nature conservation, etc.), a certain susceptibility of urban areas to dusting is formed. The role of the transport arteries of the city in the emission of resuspended dust is reflected in a separate indicator: the average daily intensity of motor vehicles on the main transport arteries in Burgas. In the selection of baseline data, a value of 10,000 vehicles/day was used as a critical threshold.

The indicator for PM pollution reflects aggregated spatial results for annual average concentrations of PM_{10} from all sources and the formation of pollution hotspots in the city of Burgas. The assessment scale is consistent with the World Health Organization's air quality guidelines and its reference levels for the allowable annual mean concentration for $PM_{2.5}$ and PM_{10} [43]. The same source states that $PM_{2.5}$ makes up between 50 and 80% of the weight of PM_{10}. Current data on the concentration of $PM_{2.5}$ in Burgas at the time of this analysis (May–June 2024) show that they are the main pollutant of ambient air in the city of Burgas [44].

The high percentage of sealed surfaces and the configuration of the built-up area create the conditions for the occurrence of higher average surface and ground air temperatures in urban areas. A systematic review of the existing scientific literature on the subject reveals a complex relationship between air pollution and urban heat islands: on the one hand, air pollution contributes to the heating of urban areas, and on the other hand, urban heat island effects influence air quality [45]. The combined effect of these two threats contributes significantly to climate change and its derivative effects in urban settings. The criterion chosen here is the mean land surface temperature measured around noon local time (based on Landsat 8 data from 30 July 2022). The choice of the time range is determined by the direct influence that the land surface temperature (LST) has on the temperature and dynamics of the ground air, and with this on the dispersion of the PM in the vertical air exchange. Comparative analysis with evening temperatures after sunset (based on data from previous observations [36]) gives us reasons to assume that the LST during daylight hours has a much more significant influence on the dusting process. Based on the obtained raster temperature values, an average LST for each LCZ cell was calculated using zonal statistics.

Table 1. Air quality indicators, parameters, scores, and data sources for geospatial analysis.

Indicators and Parameters (Calculated for Each LCZ)		Evaluation Scale	Data Used for the Analysis
1.	Sealed areas (Area in %)	Low: 0–30% Medium: 30–60% High: >60%	Spatial layer of urban green areas (*Geographica Ltd.*, *Sofia*, *Bulgaria*)
2.	Susceptibility to dust (Type of LCZ according to dominant land use)	Low: LCZ A, B, D, G Medium: LCZ 6, 9, C High: LCZ 3, 4, 5, 8, 10, E	Orthofoto image of Burgas, 2022 (*Geographica Ltd.*, *Sofia*, *Bulgaria*)
3.	PM_{10} concentrations (Annual mean concentrations, 2019)	Low: <15 $\mu g/m^3$ Medium: 5–15 $\mu g/m^3$ High: >15 $\mu g/m^3$	Municipality air quality report [46]
4.	Average land surface temperature (°C)	Low: Up to 24 °C Medium: Up to 28 °C High: Over 28 °C	Landsat 8 Satellite image [47]
5.	Traffic (Average daily traffic—number of vehicles/24 h)	Low: Up to 10,000 Medium: 10,001–25,000 High: Over 25,001	Numbers of daily traffic (*Burgas Municipality*, *Burgas*, *Bulgaria*)

Indicators for assessing green infrastructure/potential for providing regulation of air quality and reducing secondary pollution.

To reflect the role of GI on ambient air quality through the reduction in PM, a combination of indicators has been selected, appropriate to the nature of the available data and the scale of the study (Table 2). For this purpose, baseline data from the green system of the city of Burgas (https://greensystem.smartburgas.eu/, accessed on 13 August 2024) [48] were used. Important spatial factors such as the overall provision of natural environmental elements (inherited and new) and projective cover—green elements and water bodies—are taken into account. An indicator is introduced to reflect the spatial extent of the influence of green elements on their contact environment. This has been implemented by analyzing an average distance of 50 m from green areas over 1 ha. The connectivity factor increases the effectiveness of green elements in the regulation of microclimatic conditions and the improvement of the AQ. Here, the indicator takes into account the connectivity of urban parks and green areas with a spatial extent of more than 2 ha.

Urban tree vegetation has a leading role in reducing PM compared to other types of urban vegetation, which is explained by plant morphology [49]. For the conditions of the city of Burgas, the cooling effect provided by the GI is additionally important, as it mediates the reduction in PM by favoring microclimatic conditions. The indicator used here represents the area distribution (%) of the tree canopy for each LCZ grid cell. Cells with no tree cover are scored as '0'. The assessment of the indicator was carried out in several sequential steps: initial selection of tree vegetation over 3 m in height; selection of cells with an average tree vegetation height below 5 m and creation of a 25 m^2 buffer for each tree falling within these LCZs. Selection of cells with an average height of tree vegetation above 10 m and the creation of a buffer of 40 m^2 for each tree falling within these LCZs.

The study also applied additional indicators involved in the final prioritization of sites for investment in the GI (Table 3). This was implemented by introducing in the assessment (per each LCZ grid cell) information on the spatial concentration of social infrastructure facilities (health facilities, social institutions, educational facilities, kindergartens, universities, sports facilities, and playgrounds) and population number.

Table 2. UGI indicators, parameters, scores, and data sources for geospatial analysis.

Indicators and Parameters (Calculated for Each LCZ)	Evaluation Scale	Data Used for the Analysis
1. Green areas (area in %)	Low: 0–30% Medium: 30–60% High: <60%	Spatial layer of urban green areas (*Geographica Ltd.*, *Sofia*, *Bulgaria*)
2. Impact of green areas larger than 1 ha (meters)	Low: Over 300 m Medium: Up to 300 m High: Up to 100 m	
3. Connectivity of green areas larger than 1 ha (100 m distance between individual green patches)	Low: No connectivity Medium: 50–90% High: 100%	Spatial layer of urban green areas (*Geographica Ltd.*, *Sofia*, *Bulgaria*)
4. Contribution of tree vegetation to the composition of existing green areas (% canopy cover)	Low: Up to 25% Medium: Up to 50% High: over 50%	Spatial layer of urban trees/point feature/(*Geographica Ltd.*, *Sofia*, *Bulgaria*)
5. Water (presence of water bodies)	Low: No High: Yes	Orthofoto image of Burgas, 2022 (*Geographica Ltd.*, *Sofia*, *Bulgaria*)

Table 3. Prioritization indicators, parameters, scores, and data sources for geospatial analysis.

Indicators and Parameters (Calculated for Each LCZ)	Evaluation Scale	Data Used for the Analysis
1. Spatial concentration of public facilities (Number)	Low: No facilities Medium: 1–2 High: 3–4	Spatial layer of public facilities/point features(*Burgas Municipality*, *Burgas*, *Bulgaria*)
2. Population (Number)	Low: Up to 100 Medium: Up to 200 High: Over 200	Number of population by neighborhood (*Burgas Municipality*, *Burgas*, *Bulgaria*)

3. Results

3.1. Local Climate Zones

Within the urban area of Burgas City, 14 types of LCZ have been identified (Table 4, Figure 3). They are organized in territorial units of the same size and shape—a uniform grid with sides 100 m × 100 m with an area of 1 ha, which gives enough area for a site to be defined as a specific LCZ. Smaller cell sizes imply a risk that separated LCZs could be wrongly defined based on the absence of a particular element. They number 3789 in total. The LCZs were determined based on highly detailed digital models of the study area (2022). Based on these models, parameters such as density of development, percentage coverage of sealed areas, or presence of vegetation have been accurately extracted. After the LCZ classification, a field verification was performed.

Table 4. Local climate zones in Burgas.

LCZ	Number of Cells in Total	Area in %
LCZ_3 Compact low-rise buildings	28	1
LCZ_4 Open high-rise buildings	49	1
LCZ_5 Open midrise buildings	814	21
LCZ_6 Open low-rise buildings	180	5

Table 4. *Cont.*

LCZ	Number of Cells in Total	Area in %
LCZ_8 Large low-rise buildings	882	23
LCZ_9 Sparsely built	122	3
LCZ_10 Heavy industry	50	1
LCZ_A Dense trees	21	1
LCZ_B Scattered trees	246	6
LCZ_C Bush, scrub	69	2
LCZ_D Low plants	491	13
LCZ_E Bare rock or paved	196	5
LCZ_F Bare soil or sand	59	2
LCZ_G Water	582	15
Total	**3789**	**100**

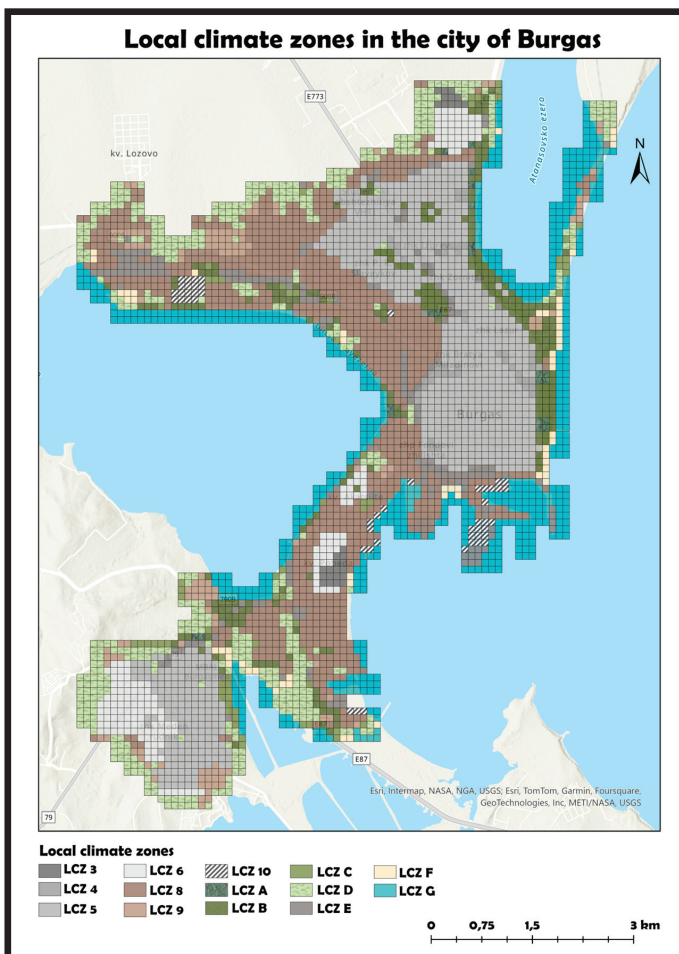

Figure 3. Local climate zones in the city of Burgas.

As shown in Table 4, according to the type of construction, the largest area is occupied by open midrise buildings (residential neighborhoods) and large low-rise buildings (industrial buildings).

3.2. Integrated Geospatial Analysis of the Balance "Air Quality Regulation Demand and Potential to Reduce Secondary Dust Pollution from the Urban Green Infrastructure" and Prioritization of Cells through Control Indicators

The spatial results of the thematic assessment of the indicators concerning the unfavorable preconditions and existing circumstances for the deterioration of the AQ are presented in Figure 4. The result is considered as degrees (low, medium, and high) of "demand to introduce measures to mitigate secondary spraying" (Figure 5). The aggregated results show a high vulnerability to dust pollution in the over-concentrated urban core and along major transport links. This is a complex result of the urban structure of Burgas in these ecological and geographical conditions and its modern functional specialization. However, with the greatest influence on the concentration of demand for air quality regulation in the central urban area are the high percentage of sealed surfaces (over 60%), the high values of pollution with PM (over 15 μg/m^3), and the concentration on busy boulevards.

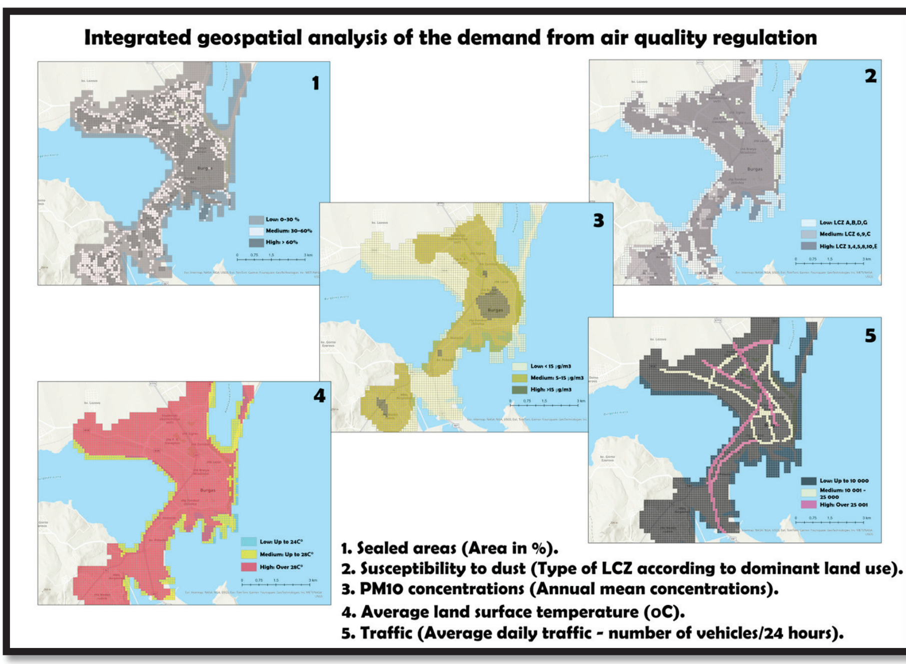

Figure 4. Integrated geospatial analysis of the demand from air quality regulation—overlay analysis.

The spatial results of the implemented indicators for the assessment of UGI, i.e., the potential to provide air quality regulation and secondary dust pollution reduction, are presented in Figure 6. The summarized results give a reason to point out that in general there is a favorable overall structure of the green system of the urban space in the city of Burgas. This is particularly evident in the northeastern parts of the city as well as on the periphery. This high potential is mainly because, in the above-mentioned areas, the percentage of greenery in the grid is high (over 60%), supported by the positive values of the other important functions of UGI: the impact and connectivity of green areas, and last but not least, the presence of water bodies (Figure 7).

The outcome of this phase of the study is the identification of grid cells/LCZs with high and medium values of "demand for air quality regulation" but with low "potential for air quality regulation"—cells that are deficient in regulatory mechanisms to mitigate secondary sputtering and need to upgrade/rebuild air quality elements. The results of the integrated analysis found that in the central areas of the city of Burgas, there are compact areas along the main boulevards where it is necessary to implement measures to mitigate secondary dust pollution through the construction of elements of the UGI. These results have been used as the basis for the subsequent steps of prioritization of the areas and spatial definition of the sites/territories for targeted intervention to build the elements of the UGI (Figure 8).

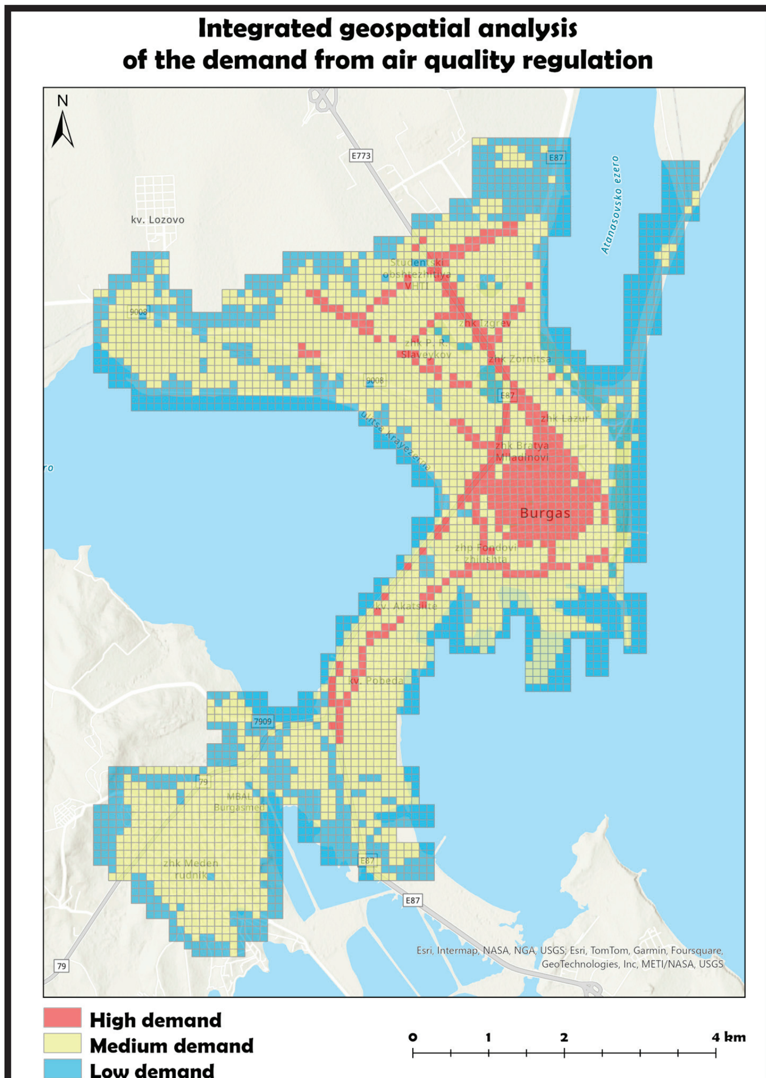

Figure 5. Integrated geospatial analysis of the demand from air quality regulation.

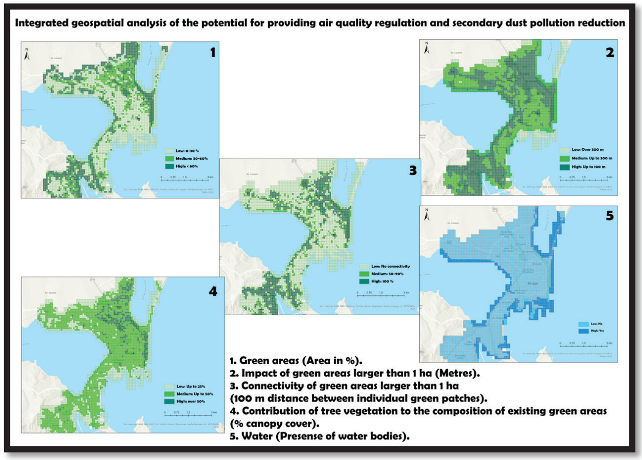

Figure 6. Integrated geospatial analysis of the potential for providing air quality regulation and secondary dust pollution reduction—overlay analysis.

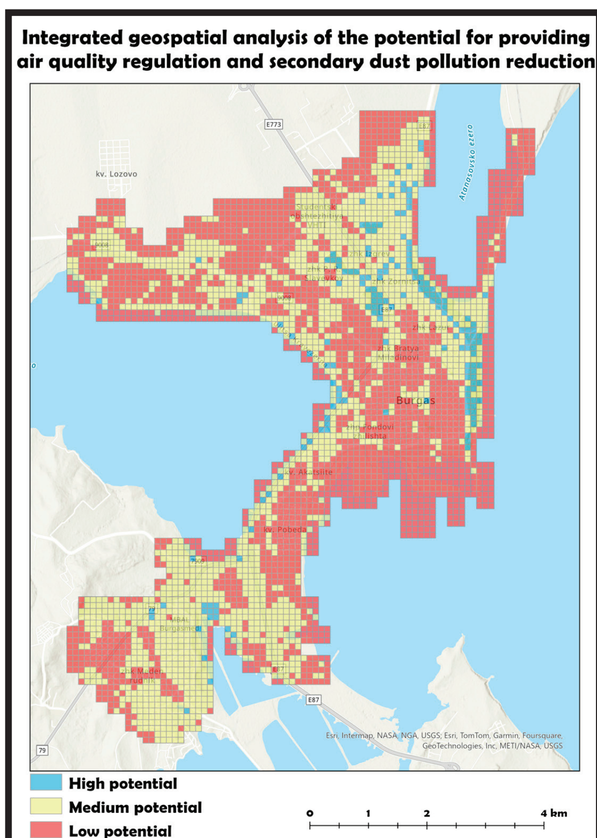

Figure 7. Integrated geospatial analysis of the potential for providing air quality regulation and secondary dust pollution reduction.

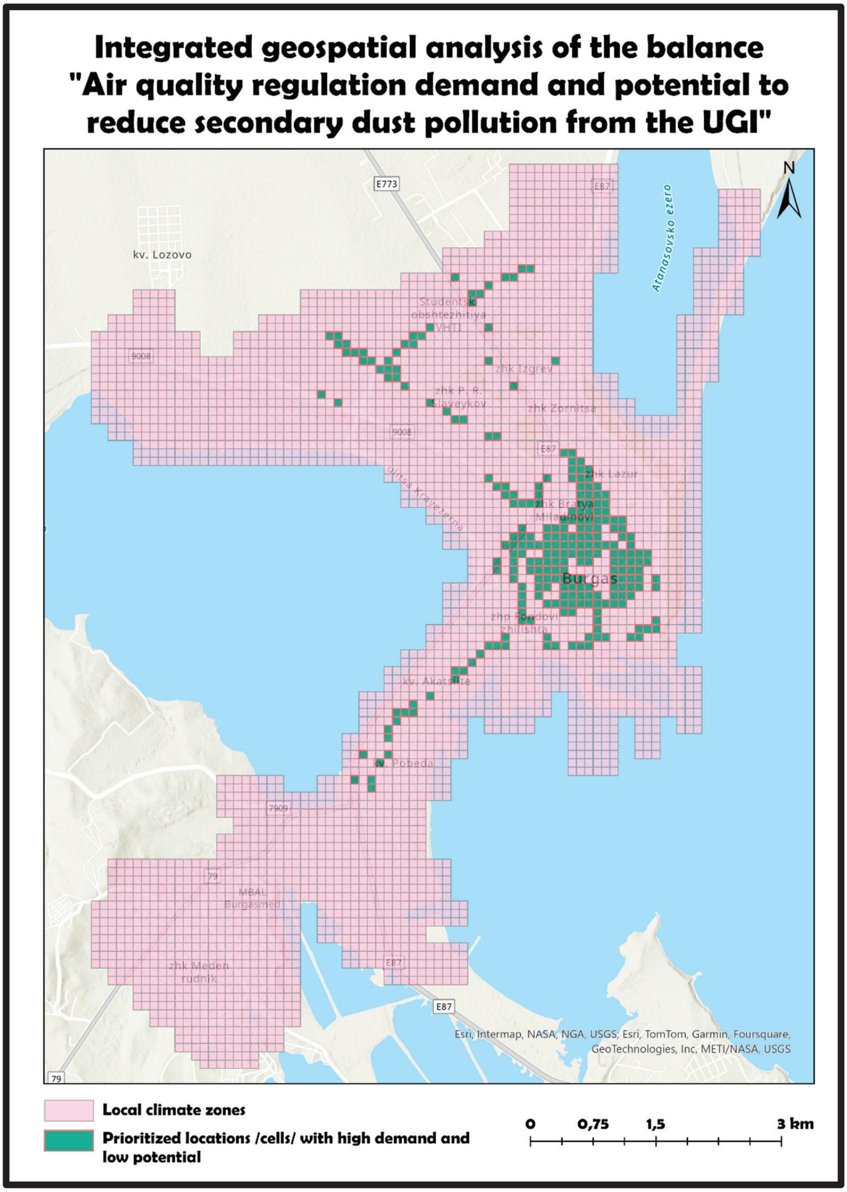

Figure 8. Integrated geospatial analysis of the balance "Air quality regulation demand and potential to reduce secondary dust pollution from the UGI".

The data obtained from the assessment of the "demand/potential" balance are subjected to secondary analysis by introducing information on the presence and spatial concentration of public social facilities and population. A total of 79 cells of priority importance for landscaping have been identified. Their total area is 0.79 km^2.

3.3. Selection of Urban Green Infrastructure Investment Locations

As a result of the complex geolocalization analysis, two groups of priority spatial locations (a total of 79 grid cells/LCZs) have been identified for investment and construction of components of the UGI.

1. Group 1 (47 LCZs)—highest priority locations: a high concentration of social facilities (three to four sites), with a population density of over 200 people per cell (relevant LCZ), with a 'high' need for the introduction of secondary dust mitigation measures, but a 'low' potential of provision from the available UGI structure.
2. Group 2 (32 LCZs)—high priority locations: a high concentration of social facilities (three to four sites), with a population density of over 200 people per cell (relevant LCZ), with a 'medium' need for the introduction of secondary dust mitigation measures, but a 'low' potential of provision from the available UGI structure (Figure 9).

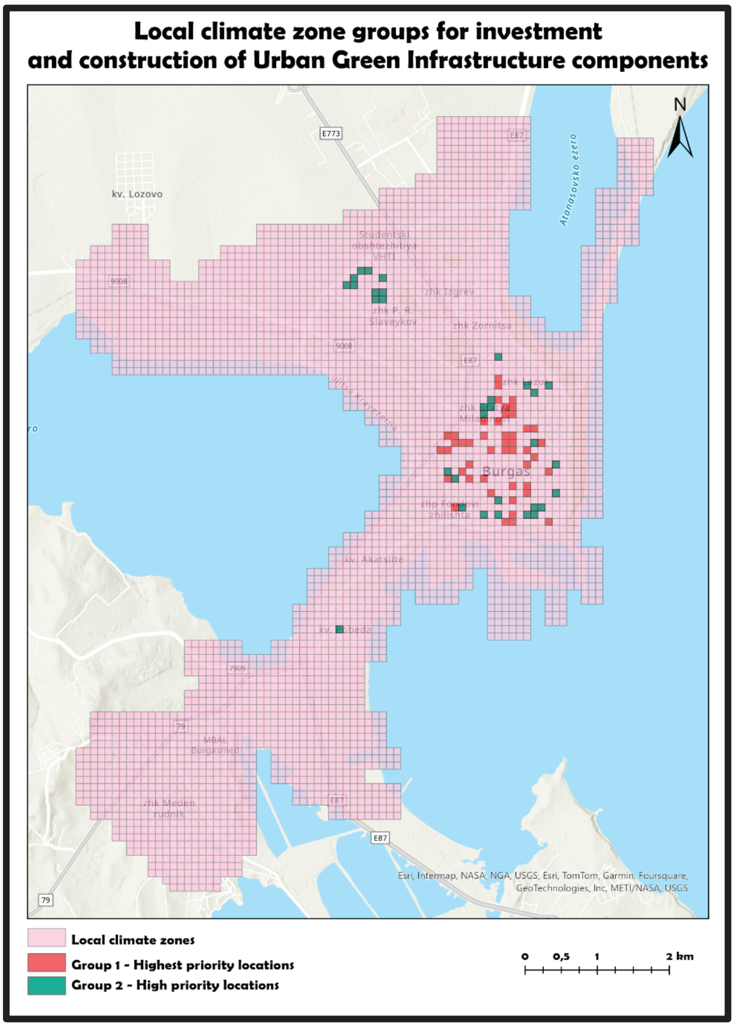

Figure 9. Local climate zone groups for investment and construction of UGI components.

A spatial analysis of potential green areas in the city of Burgas revealed that 112 identified sites are located within a 100 m radius of social facilities. Among these, 17 sites are situated within municipal educational centers, such as schools and kindergartens. Another 41 properties designated for greening fall within 100 m of educational institutions across the city. Furthermore, 75 playgrounds benefit from this proximity to the identified green areas. Within the 100 m buffer surrounding eight of the identified green spaces, there are five or more social infrastructure objects, with the highest concentration being eight near an identified area along Yanko Komitov Boulevard. This clustering of green spaces near multiple social infrastructure elements, especially near schools, kindergartens, and playgrounds, highlights their strategic importance in urban planning, offering opportunities to enhance accessibility to green areas.

Based on the above-mentioned prioritized LCZs, in close proximity to/around, 174 properties (municipal ownership only) have been identified for future planned investments in UGI. The total area of the identified areas for landscaping in the mentioned properties is 15 ha. The results were discussed with the responsible parties from the Municipality of Burgas—emphasis was placed on the disturbed areas identified in the course of the field verification (bare surfaces without vegetation or disturbed pavements—a permanent source of dust pollution). Feedback was sought from the Landscaping Directorate regarding the qualitative characterization of the green elements and the health of the vegetation in the prioritized cells. It is recommended to study the results of targeted research [50] for the selection of species for afforestation that are drought-tolerant and disease-resistant in the climatic conditions of Southeastern Bulgaria.

Spatial data for the identified landscaping locations, along with detailed attributive information, has been provided to the Burgas Municipality in convenient file formats. Some of the attributive information includes the following data: identifier, cadastral number, and ownership of the property according to the National Property Register; area of the property by cadastral map; and the area of identified landscaping areas. Information on the locations/investment areas on which a new UGI will be built or constructed to address secondary dust pollution mitigation is organized as follows (Figure 10):

- For roadside landscaping along busy urban streets/boulevards (outside the national road network).
- For spaces between blocks—public spaces with open access (publicly accessible), including city parks, gardens, squares, and spaces between city blocks that have a disturbed structure (mud patches).
- For social infrastructure facilities—outdoor school areas and those on the territory of kindergartens—municipal property.

Evidence has been collected in geolocation images which have been added to the other attribute information. In the preparation phase of the landscaping projects, the team of this study, together with the urban planners of the Burgas Municipality, will discuss the possibilities of applying innovative NBS to contribute to a reduction in secondary dust.

To extract the maximum amount of practical information to support discussions for future projects, some of the locations identified with the highest demand for investment in the construction of GI were mapped with the laser scan system GEOSLAM ZEB Horizon (Figure 11).

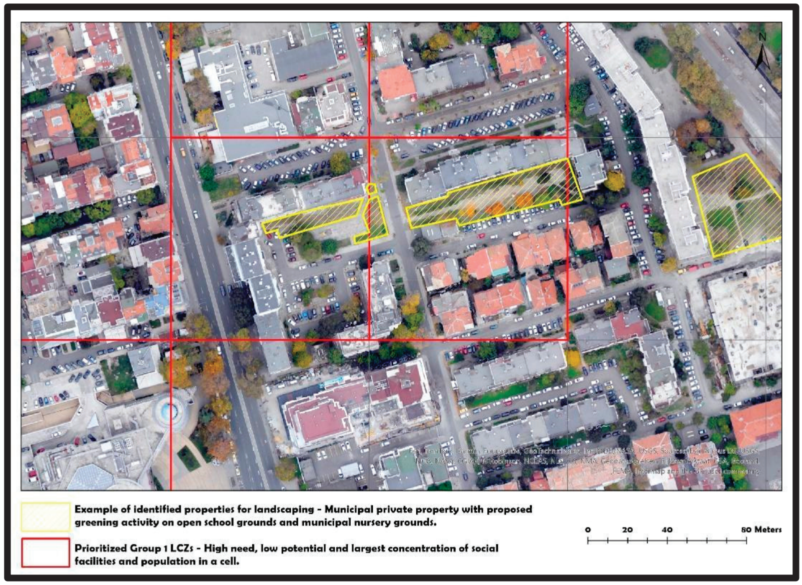

Figure 10. Example with identified properties for landscaping.

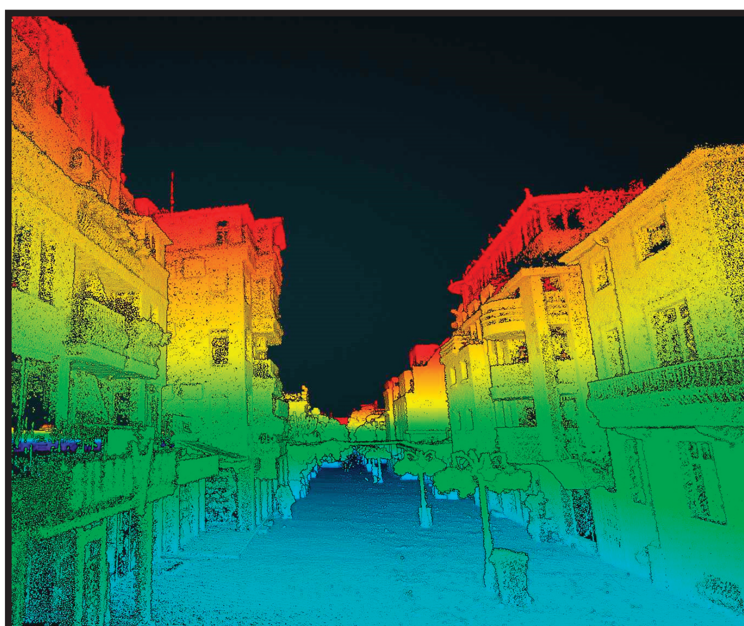

Figure 11. Locations mapped with laser scan system GEOSLAM ZEB Horizon.

4. Discussion

The assumption that GI can improve air quality is widely held in the public health [29], urban planning [51], and ES literature [52]. The UN's Environmental-Economic Accounting offers vegetation as an environmentally friendly solution to reduce air pollution [53]. The main mechanisms by which air pollution can be reduced by vegetation include deposition and dispersion. However, depending on vegetation structure (plant height, leaf density), site context (e.g., street canyon geometry, distance to emission source), and prevailing meteorological conditions (such as wind speed and direction), the effects of ventilation and dispersion may be thwarted [54]. This is a serious challenge in the design of park spaces [10,55].

The effectiveness of UGI in reducing dust pollution can be a controversial topic and draws attention to the role of urban microclimate on environmental quality. However, urban climate data are tracked from a limited number of monitoring sites and present a general picture with a range of variability in the values of urban climate elements. Such information is unrecognizable by urban planners and landscape architects and is difficult to incorporate into the planning of specific urban spaces, especially in response to local urban challenges. Local microclimatic research requires significant financial and time resources. It is justified when they are conducted for the planning of specialized NBS adapted to a problem location, or in a private project when the site is of great public importance. However, in developing a unified framework for city landscaping and discussing its financing, they are inapplicable.

Our response to this challenge is to conduct research that directly links green infrastructure to local climate zoning. This approach provides a scientific basis for correctly capturing the causal relationship between urban structures, microclimate, and the ecological environment. The approach offers information for taking actions whereby influencing elements of the urban fabric (greening in specific properties in terms of area and configuration) influences microclimatic conditions and AQ.

In essence, our approach creates an information basis for building a unified city-wide approach to planning and implementing landscaping interventions in a form that is understandable to all parties involved in the process (managers, administration, urban planners, landscapers, and designers). However, all of this depends on one precondition—precision in defining the LCZ as the basic urban information unit to reflect urban heterogeneity (cover types and urban geometry) and its corresponding environmental quality. Specific arguments in this direction are outlined below.

4.1. The Local Climate Zones and Regulating Ecosystem Services

If urban structure and surface heterogeneity are major determinants of pollutant retention and secondary dust generation, then microclimatic conditions (in an environment of high urban heterogeneity) are significant mediating factors of influence on AQ as a general outcome. The use of LCZ as a unifying framework for tracking spatial and functional relationships between urban structures, microclimate, and AQ, in our view, brings numerous advantages in research informing the development of citywide strategies and action plans. We have approached this research with the understanding that LCZ can provide us with the much-needed causal link between urban structure and ESs that Marques, 2022 [14] draws attention to.

Among the important advantages is the possibility of comparability between areas within the city, as well as an in-depth analysis of a given location in the context of the characteristics of its contact areas and against the background of the functioning of the urban structure as a whole. This approach also provides an opportunity to include in the analyses information concerning local climatic features (in our case through land surface temperature) which regular urban climate monitoring cannot provide, given the limited coverage of the network and the different focus of the observations. LCZs can also facilitate discussion of urban climate change in the context of global climate change. The exclusion of direct data from local climate observations is one of the main drawbacks of the methodology proposed here.

The inconvenience, in this case, is due to the fact that all urban planning activities in Bulgaria are tailored to urban units established for each respective city, which are of different sizes and purposes. However, the LCZ approach offers a good typology option that is understandable for urban planners and landscape designers and brings the obvious advantages of a possible change of scale of the study (when changing the dimensionality of the cells). The approach also implies the identification of cells with a higher contribution to the provision of regulating ESs—this is a good information base that can be combined with further analyses of vegetation structure types and ratios to built-up area types for the optimal provision of regulation. This must take into account the potential environmental "contribution" that the species will be able to make concerning maintenance costs according to the principle of "the right plant in the right place and with the right management" [28].

However, the dimensionality of the LCZ cells mentioned here is fundamental to the precision of the geolocalization analysis. The correct conduct of thematic assessments depends to a large extent on the provision and representativeness of source data at the spatial extent of the basic unit of information thus defined. Therefore, the verification stage plays an important role in eliminating possible errors. This requires high-precision photogrammetric information and a longer period of field observations. The high heterogeneity of the city of Burgas forced a reduction in the cell size to 100 × 100 m to enter the highest possible detail for surface features.

In the course of processing the data provided, several deficiencies were identified that impacted the analysis. Some of the properties fall outside the boundaries of designated LCZs, which has led to their exclusion. In addition, some of the identified areas overlap with areas that are not municipally owned, limiting their ability to be used within the project. The spatial limitation of the grid cells resulted in instances where identified properties fell only partially within their scope, limiting the accuracy of the analysis. These factors highlight the need for additional data verification and correction to ensure greater accuracy and reliability of the analysis.

4.2. Demand and Provision of ESs—Selection of Indicators

Our research adopts the concept of Larondelle et al., 2016 [56] for a transferable methodology for informed planning processes. Our study reveals spatial mismatches in the need for and supply of regulating ESs from the GI. This approach is well suited for discussing urban transformations with stakeholders and the local public and forms a clearer understanding of ESs from the GI. Last but not least, the results of this approach reinforce the role of GI in ensuring the quality of life and the key need (for Bulgarian cities) for green elements to be planned and managed as 'infrastructure'.

However, the specificity we are looking for—the size of areas, locations in the urban structure, and lasting cause-effect relationships for the AQ in that locality—is dependent on a proper selection of indicators to reflect urban conditions and sustainable sources of information. The selection of indicators in the geospatial analysis here is tailored to the capacity of urban governance to provide available data, to update the information, and to periodically assess (the LCZ approach further facilitates this) important spatial dependencies, functional causal relationships, and deficits in the mix of grey and green infrastructure. This flexibility of the methodology is much needed given the high propensity to change urban heterogeneity. In a subsequent extension of the study, we find it appropriate to incorporate information on wind direction and speed, building height and building orientation relative to wind direction, internal structural features of vegetation cover, and seasonal changes in vegetation cover.

4.3. Landscaping of Urban Properties—General or Individual Approach

In considering a unified approach to urban greening, the issue of urban land ownership and the coordination of the allocation of green space in private and public spaces is essential. The city's authority for UGI interventions is limited to municipally owned land. Nevertheless, the database we developed is comprehensive and the city authority could use it to communicate with the landowners. Local government communication with stakeholders and private parties is important and can provide the necessary consistency in the characteristics of adjacent properties to achieve the desired heterogeneity, connectivity, and overall coverage providing UGI regulation of the AQ.

5. Conclusions

This study uses the urban local climate zones as a unified framework for geolocation analysis of Burgas City, selecting sites where UGI interventions can address public needs for AQ regulation and secondary dust reduction. In six methodological steps, with public information and in direct consultations with municipal management, 174 municipally owned sites suitable for UGI intervention were assessed, prioritized, and mapped. The Burgas Municipality has implemented the results in ongoing landscaping measures in support of the Burgas Municipality's AQ Improvement Program. The results provide a good basis for communication with the municipal leadership, private landowners, and business entities for cooperation in expanding the connectivity and effectiveness of UGI to permanently improve AQ.

The proposed methodological approach has a promising potential for discussing local urban challenges in maintaining a people-friendly living environment. The results are understandable for a wide range of stakeholders and actors and applicable for immediate integration into sustainable urban planning activities.

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

Funding: This study is financed by the European Union-NextGenerationEU through the National Recovery and Resilience Plan of the Republic of Bulgaria, project No. BG-RRP-2.004-0008-C01.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request. The raw data supporting the conclusions of this article will be made available by the authors on request.

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

References

1. United Nations. Available online: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (accessed on 13 August 2024).
2. Behnisch, M.; Krüger, T.; Jaeger, J.A.G. Rapid rise in urban sprawl: Global hotspots and trends since 1990. *PLoS Sustain. Transform.* **2022**, *1*, e0000034. [CrossRef]
3. Grêt-Regamey, A.; Galleguillos-Torres, M.; Dissegna, A.; Weibel, B. How urban densification influences ecosystem services—A comparison between a temperate and a tropical city. *Environ. Res. Lett.* **2020**, *15*, 075001. [CrossRef]
4. Wang, W.; Wei, H.; Hassan, H.; He, X. Research progress and prospects of urban resilience in the perspective of climate change. *Front. Earth Sci.* **2024**, *12*, 1247360. [CrossRef]
5. Davide, G.; Chiara, C.; Linda, Z.; Blal, A.E. *Planning for Ecosystem Services in Cities*; Springer: Cham, The Netherlands, 2019. [CrossRef]
6. Kull, C.A.; de Sartre, X.A.; Castro-Larrañaga, M. The political ecology of ecosystem services. *Geoforum* **2015**, *61*, 122–134. [CrossRef]
7. Yu, C.; Hien, W.N. Thermal benefits of city parks. *Energy Build.* **2006**, *38*, 105–120. [CrossRef]
8. Chang, C.-R.; Li, M.-H. Effects of urban parks on the local urban thermal environment. *Urban. For. Urban. Green.* **2014**, *13*, 672–681. [CrossRef]
9. Peng, J.; Dan, Y.; Qiao, R.; Liu, Y.; Dong, J.; Wu, J. How to quantify the cooling effect of urban parks? Linking maximum and accumulation perspectives. *Remote Sens. Environ.* **2021**, *252*, 112135. [CrossRef]
10. Stark da Silva, P.W.; Duarte, D.H.S.; Rahman, M.A.; Rotzer, T.; Pauleit, S. Testing Strategies for Planting Design in Urban Squares to Improve Human Comfort throughout the Seasons. *Atmosphere* **2024**, *15*, 870. [CrossRef]
11. Cortinovis, C.; Geneletti, D. Ecosystem services in urban plans: What is there, and what is still needed for better decisions. *Land Use Policy* **2018**, *70*, 298–312. [CrossRef]
12. Scott, M.; Lennon, M.; Haase, D.; Kazmierczak, A.; Clabby, G.; Beatley, T. Nature-based solutions for the contemporary city/Re-naturing the city/Reflections on urban landscapes, ecosystems services and nature-based solutions in cities/Multifunctional green infrastructure and climate change adaptation: Brownfield greening as an adaptation strategy for vulnerable communities?/Delivering green infrastructure through planning: Insights from practice in Fingal, Ireland/Planning for biophilic cities: From theory to practice. *Plan. Theory Pract.* **2016**, *17*, 267–300. [CrossRef]

13. Haase, D. Integrating Ecosystem Services, Green Infrastructure and Nature-Based Solutions—New Perspectives in Sustainable Urban Land Management Combining Knowledge about Urban Nature for Action. In *Sustainable Land Management in a European Context, Human-Environment Interactions 8*; Weith, T., Gaasch, N., Strauß, C., Barkmann, T., Rogga, S., Zscheischler, J., Eds.; Springer: Berlin/Heidelberg, Germany, 2021. [CrossRef]
14. Marques, A.L.; Alvim, A.T.B.; Schröder, J. Ecosystem Services and Urban Planning: A Review of the Contribution of the Concept to Adaptation in Urban Areas. *Sustainability* **2022**, *14*, 2391. [CrossRef]
15. Fang, X.; Li, J.; Ma, Q. Integrating green infrastructure, ecosystem services and nature-based solutions for urban sustainability: A comprehensive literature review. *Sustain. Cities Soc.* **2023**, *98*, 104843. [CrossRef]
16. Almenar, J.B.; Elliot, T.; Rugani, B.; Philippe, B.; Gutierrez, T.N.; Sonnemann, G.; Geneletti, D. Nexus between nature-based solutions, ecosystem services and urban challenges. *Land. Use Policy* **2021**, *100*, 104898. [CrossRef]
17. Dorst, H.; van der Jagt, A.; Raven, R.; Runhaar, H. Urban greening through nature-based solutions—Key characteristics of an emerging concept. *Sustain. Cities Soc.* **2019**, *49*, 101620. [CrossRef]
18. Kabisch, N.; Frantzeskaki, N.; Hansen, R. Principles for urban nature-based solutions. *Ambio* **2022**, *51*, 1388–1401. [CrossRef] [PubMed]
19. Holt, R.A.; Mears, M.; Maltby, L.; Warren, P. Understanding spatial patterns in the production of multiple urban ecosystem services. *Ecosyst. Serv.* **2015**, *16*, 33–46. [CrossRef]
20. Raymond, C.M.; Frantzeskaki, N.; Kabisch, N.; Berry, P.; Breil, M.; Nita, M.R.; Geneletti, D.; Calfapietra, C. A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environ. Sci. Policy* **2017**, *77*, 15–24. [CrossRef]
21. Wang, Y.-C.; Shen, J.-K.; Xiang, W.-N. Ecosystem service of green infrastructure for adaptation to urban growth: Function and configuration. *Ecosyst. Health Sustain.* **2018**, *4*, 132–143. [CrossRef]
22. Balzan, M.V.; Zulian, G.; Maes, J.; Borg, M. Assessing urban ecosystem services to prioritize nature-based solutions in a high-density urban area. *Nat. Based Solut.* **2021**, *1*, 100007. [CrossRef]
23. Ministry of Environment and Water: National Environment Strategy, Bulgarian Biodiversity Strategy & Environmental Protection Act. Available online: https://www.moew.government.bg/en/ (accessed on 13 August 2024).
24. Association of Municipalities in Bulgaria. Available online: https://www.namrb.org/bg/aktualno/naratchnik-za-zelena-infrastruktura (accessed on 13 August 2024).
25. Croeser, T.; Garrard, G.; Sharma, R.; Ossola, A.; Bekessy, S. Choosing the right nature-based solutions to meet diverse urban challenges. *Urban. For. Urban. Green.* **2021**, *65*, 127337. [CrossRef]
26. Program for Improving the Quality of the Atmospheric Air of the Municipality of Burgas for the Period 2021–2027. Available online: https://www.burgas.bg/bg/programi/predvaritelen-variant-na-programa-za-podobryavane-kachestvoto-na-atmosferniya-vazduha-na-obshtina-burgas-za-perioda-2021-2027-g/ (accessed on 13 August 2024).
27. Sofia, D.; Gioiella, F.; Lotrecchiano, N.; Giuliano, A. Mitigation strategies for reducing air pollution. *Environ. Sci. Pollut. Res.* **2020**, *27*, 19226–19235. [CrossRef] [PubMed]
28. Ferrini, F.; Fini, A.; Mori, J.; Gori, A. Role of Vegetation as a Mitigating Factor in the Urban Context. *Sustainability* **2020**, *12*, 4247. [CrossRef]
29. Diener, A.; Mudu, P. How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective-with implications for urban planning. *Sci. Total Environ.* **2021**, *796*, 148605. [CrossRef] [PubMed]
30. Muh, B.; Baharuddin, P.; Sri, S.; Alimuddin, H.; Eymal, D. The effect of vegetation in reducing air pollution in an urban environment: A review. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1253*, 012105. [CrossRef]
31. Lindén, J.; Gustafsson, M.; Uddling, J.; Watne, A.; Pleijel, H. Air pollution removal through deposition on urban vegetation: The importance of vegetation characteristics. *Urban. For. Urban. Green.* **2023**, *81*, 127843. [CrossRef]
32. National Statistical Institute. 2023. Available online: https://nsi.bg/en (accessed on 13 August 2024).
33. Plan for Integrated Development of Burgas Municipality. Available online: https://plan.smartburgas.eu/%D0%BF%D0%B8%D1%80%D0%BE-2021-2027/ (accessed on 13 August 2024).
34. Meteoblue. 2024. Available online: https://www.meteoblue.com/bg/%D0%B2%D1%80%D0%B5%D0%BC%D0%B5%D1%82%D0%BE/historyclimate/climateobserved/%D0%91%D1%83%D1%80%D0%B3%D0%B0%D1%81_%D0%91%D1%8A%D0%BB%D0%B3%D0%B0%D1%80%D0%B8%D1%8F_732770 (accessed on 13 August 2024).
35. Stewart, I.D.; Oke, T.R. Local Climate Zones for Urban Temperature Studies. *Bull. Am. Meteor. Soc.* **2012**, *93*, 1879–1900. [CrossRef]
36. Dimitrov, S.; Borissova, B.; Iliev, M.; Semerdzhieva, L. Application of thermal photogrammetry in local climate zones definition for urban heat island effect assessment and mapping of the city of Burgas, Bulgaria. In Proceedings of the Ninth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2023), Ayia Napa, Cyprus, 3–5 April 2023. [CrossRef]
37. Aslam, A.; Ahmad Rana, I. The use of local climate zones in the urban environment: A systematic review of data sources, methods, and themes. *Urban. Clim.* **2022**, *42*, 101120. [CrossRef]
38. Brusseleers, L.; Nguyen, V.G.; Vu, K.C.; Huy Dung, H.; Somers, B.; Verbist, B. Assessment of the impact of local climate zones on fine dust concentrations: A case study from Hanoi, Vietnam. *Build. Environ.* **2023**, *242*, 110430. [CrossRef]

39. Han, J.; Hu, Z.; Sajadi, P.; Li, S.; Zhang, Y.; Cui, R.; Pilla, F. Evaluating urban development in China's resource-based cities: A new perspective using nighttime light data. *Int. J. Digit. Earth* **2024**, *17*, 2349747. [CrossRef]
40. Zhiyanski, M.; Nedkov, S.; Mondeshka, M.; Yarlovska, N.; Borisova, B.; Vassilev, V.; Bratanova-Doncheva, S.; Gocheva, K.; Chipev, N. Methodology for Assessment and Mapping of Urban Ecosystems Condition and Their Services in Bulgaria. 2018, ISBN 978-619-7379-03-7. Available online: https://www.researchgate.net/publication/322313619_2_METHODOLOGY_FOR_ASSESSMENT_AND_MAPPING_OF_URBAN_ECOSYSTEMS_CONDITION_AND_THEIR_SERVICES_IN_BULGARIA_ISBN_978-619-7379-03-7 (accessed on 5 September 2024).
41. Anton, P.; Stelian, D.; Bilyana, B.; Martin, I. Research and Mapping of the Urban Heat Island Effect on the Territory of Sofia and Study of Good Practices to Mitigate Its Manifestation. 2019. Available online: https://www.researchgate.net/publication/337830859_PROUCVANE_NA_DOBRI_PRAKTIKI_ZA_TOPLINNITE_OSTROVI_NA_TERITORIATA_NA_STOLICNA_OBSINA_IZSLEDVANE_I_KARTOGRAFIRANE_NA_EFEKTA_NA_GRADSKIA_TOPLINEN_OSTROV_NA_TERITORIATA_NA_SOFIA_I_PROUCVANE_NA_DOBRI_PRAKT?channel=doi&linkId=5dede70d299bf10bc34c5eea&showFulltext=true (accessed on 5 September 2024).
42. Smart Burgas 2024. Available online: https://smartburgas.eu/bg (accessed on 13 August 2024).
43. World Health Organization. WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. World Health Organization. 2021, License: CC BY-NC-SA 3.0 IGO. Available online: https://iris.who.int/handle/10665/345329 (accessed on 13 August 2024).
44. IG Air Quality Data. Available online: https://www.iqair.com/bulgaria/burgas (accessed on 13 August 2024).
45. Anbazu, J.; Antwi, N.S. Nexus Between Heat and Air Pollution in Urban Areas and the Role of Resilience Planning in Mitigating These Threats. *Adv. Environ. Eng. Res.* **2023**, *4*, 47. [CrossRef]
46. Burgas Municipality. Available online: https://www.burgas.bg/en/ (accessed on 1 June 2024).
47. USGS Earth Explorer. Available online: https://earthexplorer.usgs.gov/ (accessed on 1 June 2024).
48. Green System—Smart Burgas. Available online: https://greensystem.smartburgas.eu/ (accessed on 13 August 2024).
49. Grylls, T.; van Reeuwijk, M. How trees affect urban air quality: It depends on the source. *Atmos. Environ.* **2022**, *290*, 119275. [CrossRef]
50. Georgiev, G.; Georgieva, M.; Mirchev, P.; Zhiyansky, M. *Major Insect Pests and Fungal Pathogens of Woody and Shrub Vegetation in Urban Ecosystems*; Hlorind Ltd.: Sofia, Bulgaria, 2017; p. 54.
51. Huang, Y.; Lei, C.; Liu, C.-H.; Perez, P.; Forehead, H.; Kong, S.; Zhou, J.L. A review of strategies for mitigating roadside air pollution in urban street canyons. *Environ. Pollut.* **2021**, *280*, 116971. [CrossRef] [PubMed]
52. Veerkamp, C.J.; Schipper, A.M.; Hedlund, K.; Lazarova, T.; Nordin, A.; Hanson, H.I. A review of studies assessing ecosystem services provided by urban green and blue infrastructure. *Ecosyst. Serv.* **2021**, *52*, 101367. [CrossRef]
53. United Nations, "System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA)" (White Cover Publication, 2021). Available online: https://seea.un.org/content/system-environmental-economic-accounting-ecosystem-accounting-white-cover-version (accessed on 20 September 2023).
54. Venter, Z.S.; Hassani, A.; Stange, E.; Schneider, P.; Castell, N. Reassessing the Role of Urban Green Space in Air Pollution Control. *Proc. Natl. Acad. Sci. USA* **2024**, *121*, e2306200121. [CrossRef]
55. Xing, J.; Brimblecombe, P. Trees and parks as "the lungs of cities". *Urban. For. Urban. Green.* **2020**, *48*, 126552. [CrossRef]
56. Larondelle, N.; Lauf, S. Balancing demand and supply of multiple urban ecosystem services on different spatial scales. *Ecosyst. Serv.* **2016**, *22 Pt A*, 18–31. [CrossRef]

land

MDPI

Article

Reduce Speed Limits to Minimize Potential Harm and Maximize the Health Benefits of Street Trees

Xiaoqi Feng [1,2,3], Michael Navakatikyan [1,2] and Thomas Astell-Burt [2,4,*]

[1] School of Population Health, University of New South Wales (UNSW), Sydney, NSW 2052, Australia; xiaoqi.feng@unsw.edu.au (X.F.); m.navakatikyan@unsw.edu.au (M.N.)
[2] Population Wellbeing and Environment Research Lab (PowerLab), Sydney, NSW 2008, Australia
[3] The George Institute of Global Health, Sydney, NSW 2000, Australia
[4] School of Architecture, Design and Planning, University of Sydney, Sydney, NSW 2006, Australia
* Correspondence: thomas.astell-burt@sydney.edu.au

Abstract: Urban greening is threatened by the concern that street trees increase traffic-related injury/death. Associations between all serious and fatal traffic crashes and street tree percentages were examined in Sydney, Australia. Associations were adjusted for confounding factors relating to driver behavior (speeding, fatigue, and use of alcohol) and road infrastructure, including alignment (e.g., straight, curved), surface condition (e.g., dry, wet, ice), type (e.g., freeway, roundabout), and speed limit. Models indicated that 10% more street trees were associated with 3% and 20% higher odds of serious or fatal injuries and 20% tree collisions on roads of any speed, respectively. However, further analysis stratified by speed limit revealed contrasting results. Along roads of 70 km/h or greater, 10% more street trees were associated with 8% higher odds of serious or fatal injury and 25% higher odds of death. Comparable associations were not found between street trees and serious or fatal injuries along roads below 70 km/h. Reducing speed limits below 70 km/h saves lives and may mitigate risks of serious or fatal traffic accidents associated with street trees, enabling greener, cooler, healthier cities.

Keywords: green space; road traffic accidents; road traffic mortality; disability; death

Citation: Feng, X.; Navakatikyan, M.; Astell-Burt, T. Reduce Speed Limits to Minimize Potential Harm and Maximize the Health Benefits of Street Trees. *Land* **2024**, *13*, 1815. https://doi.org/10.3390/land13111815

Academic Editors: Luca Battisti, Fabrizio Aimar and Federico Cuomo

Received: 21 August 2024
Revised: 11 October 2024
Accepted: 14 October 2024
Published: 1 November 2024

1. Introduction

Ample evidence shows that urban greening is crucial for fighting climate change and improving population health. Street trees especially mitigate urban heat islands [1,2] and encourage active transport, including walking [3,4], which studies show are good for our health and environment [5,6]. Given the benefits of green space and street trees, cities around the world are making large and durable investments in tree planting in Sydney [7], Barcelona [8], Vancouver [9], and Seattle [10]. However, the planting and preservation of street trees face considerable attitudinal and systemic challenges from other sectors, including transport planning. There is a concern that street trees may increase the risk of serious injury and death along roads, in part due to the consequences of errant vehicles crashing into trees and also because of proximal factors (e.g., trees reducing visibility that could contribute to more serious crashes not necessarily involving collisions with trees). A literature review [11] identified eight out of ten studies reporting the presence of street trees as a predictor of crash likelihood or severity.

Evidence is unclear on the extent to which the risk presented by street trees to injury and death from traffic crashes may be attributable to other factors that are well-known to affect crash risk and, in some cases, severity, such as wet weather [12], speeding [13], fatigue [14,15], and driving under the influence of alcohol [16]. Moreover, there is a counter-argument to the aforementioned concern from other studies that indicate street trees perform a traffic-calming function, as drivers perceive them as presenting risk and thereby drive more carefully and slowly, reducing the number of crashes occurring and preventing a proportion of the impact on health and disability [17,18]. Furthermore, decades of evidence point to psychologically restorative benefits of contact with nature, providing relief from stress and renewing cognitive capacities depleted through adaptation to stressful experiences such as driving [19,20]. Therefore, street trees may reduce risk-taking behavior that leads to more serious crashes by helping to ameliorate drivers' stress and frustration, with several studies reporting supportive findings [11]. Evidently, these perceptions of risk and restorative effects on driver psychology may be contingent upon how fast the roads are on which vehicles travel. Along roads with lower speed limits, drivers have greater opportunities to appreciate the leafier streetscapes, whereas, along high-speed roads such as motorways/freeways, a greater focus on traffic is needed due to the reduced time in which to make key decisions and the far greater danger involved in crashes [13].

The evidence on street trees and risks of injury and death from traffic crashes is therefore neither clear nor as well-established as that for mental, physical, and social health benefits of street trees [3,21–29] and green spaces more generally [19,20]. However, the transport sector's public health-related concerns must be treated seriously, transparently, and subjected to interrogation with the best available data for decision-making in transport planning if street tree planting and preservation is to be a sustainable policy option. In this study, we test two hypotheses. We hypothesize that (1) after adjusting for confounding factors (e.g., behavioral risk factors, adverse weather conditions, road complexity), the presence of street trees reduces the risk of serious injury and/or death because of psychologically calming influences on traffic speed and driver behavior. We also hypothesize that (2) these benefits will mainly tend to occur along roads at lower speeds through the negation of risk-taking behaviors, whereas the risks involved in driving along faster roads are built-in due to fast-flowing traffic.

2. Methods

2.1. Traffic Crash Data

Center for Road Safety, Transport for NSW (Australia) provided anonymous crash, traffic unit, and person records from the center crash database for the years 1999 to 2020 in the Sydney Metropolitan area (approximately 5 million residents). For the analysis, we selected five years of data, from 2016 to 2020, for two reasons: (a) the latest data are more relevant to the current green space information available to us, and (b) from October 2014, the reporting of crashes changed, instead of all crashes being investigated by Police, there were currently investigated by Police and by self-reporting. People involved in crashes where a vehicle was towed or a person injured are still required, by law, to report the crash to NSW Police. However, NSW Police are no longer required to attend the crash scene and investigate for tow away crashes where nobody has been injured or killed.

The crash data for the Sydney Metropolitan area had 61,867 entries between 2016 to 2020. From these, the following were unselected in sequential order: 152 crashes with parked vehicles running away, as irrelevant to the aim of the study; 3385 crashes with road area data absent; and another 853 crashed with road area < 800 sq m, as these cases present challenges in reliably identifying nearby street tree canopy cover. After these exclusions, the final analytical sample consisted of 57,477 crashes.

The data contained a range of outcome variables describing the degree of crash by damage to people or vehicles, including a number of fatal, serious, moderate, and minor or no injuries (tow-away). Two kinds of injury variables are available: first, the total number of different types of injuries per crash, and second, the degree of crash detailed, only the most severe type of injury in a crash or none. We chose the second type for the analysis, as it allows us to assess the percentage of crashes related to an injury with respect to the total number of crashes. For the modeling, in addition to fatal injury, we created two combined variables: (1) crashes with fatal or serious injury and (2) crashes with any injury, including fatal. Multiple combinations of the injuries were used because the raw analysis has shown different trends for death and serious injuries versus moderate and minor injuries with a potential for masking each other.

The last variable for the analysis is the occurrence of a car in crash hitting trees or bush during the first or the second hit of an object, or hitting some other object, derived from data on traffic units involved in crash. The latter was expected and proved to be dependent on percentage of trees in area of crash and served as a quality control for the analysis.

2.2. Street Tree Canopy Cover Within the Road Area Where Crashes Occurred

The main index for the green space—the percentage of trees—is the ratio of tree canopy area per road area within a buffer around each crash.

The tree canopy area is represented by a layer of Geoscape (Canberra, Australia) satellite data with 2 m resolution, which covers most of the Sydney Metropolitan area but not some of the outskirts. The road area layer was sourced from the Department of Planning and Environment (New South Wales, Australia) polygon dataset. This covers the actual road area plus 4 m on either side for the nature strip (owned by the local council) and also another 4 m on adjacent properties. As some roads have different numbers of lanes, the widths of roads will vary.

Each crash is used as the centroid for the crash buffer. An initial 20-m radius circular buffer has been used as a balance to allow for varying road widths. In some cases, the final buffer may be clipped to less than the 20 m radius due to a smaller road width or if the crash is not geocoded in the center of the road. This is why the buffer road area can vary from crash to crash. The buffer is spatially joined with the tree canopy layer and the road area layer, and the percentage of trees is calculated. The theoretical maximum RA within a 20-m radius is 1257 m^2. If the road area is smaller than 800 m^2, it was deemed to be unreliable with respect to the value of the percentage of trees as it is a ratio. In this case, the percentage of trees is calculated with the use of a 30-m radius buffer. If the road area is still less than 800 m^2, the 40-m radius buffer is used.

Finally, all remaining crashes with road areas less than 800 m^2 were unselected from the analysis. The optimal threshold of 800 m^2 was found using a reduction in deviance for the models with a threshold varying from 0 to 1200 with the step of 100 m^2. Reduction in deviance was obtained in logistic regression predicting a car hitting a tree or bush in the first or second hit of the object during the crash. (Details of threshold selection are in Supplementary Table S1). The final dataset contained buffers of 20 (n = 55,469), 30 (n = 1451), and 40 m radius (n = 557) with mean road area of 1151 m^2, coefficient of variation 9.7%, median = 1166 m^2, i.e., almost no skew, with maximum and minimum of 800 and 2347 m^2. The mean percentage of tree area was 8.2% (CV = 168%), substantially right-skewed (Median = 1.9%).

Three versions of the percentage of street tree percentage variable were tested: (1) continuous variable with a unit value equal to 10%; (2) variable with ten categories from 0–4.9% with step 5% to 45%+ and (3) variable with five categories: 0–4.9%, 5–9.9%, 10–19.9%, 20–34.5% and 35%+. The last variable structure was motivated by a progressively small number of crashes in the 10-categories variable and incidentally by joining categories with similar raw effects. Most modeling was performed with continuous variables, while most raw analysis was performed with ten category variables.

2.3. Statistical Analysis

Raw data analysis provided frequencies for categorical data and frequencies for different injuries per categorical variable. The calculations and data manipulations were performed using the SAS Enterprise Guide (Version 8.2 Update 1 (8.2.1.1223 (32 bit) Copyright © 2015 by SAS Institute Inc., Cary, NC, USA). Logistic regression for binary crash outcomes was fitted in MLwiN software Version 3.05 [30] using Markov Chain Monte Carlo (MCMC) estimation with burn-in/chain of 3000/20,000 iterations [31,32]. Model fits were compared where needed by the deviance information criterion (DIC), which is an output of the MCMC procedure. To compare the fits, the change in DIC relative to the smallest DIC value (which is the indicator of the best model) was calculated (ΔDIC). Original data were read into Enterprise Guide, exported to Stata/SE (Version 15.1 for Windows StataCorp LLC, College Station, TX, USA), and imported into MLwiN from the Stata file. The modeling went in three steps: two exploratory analyses and the final modeling.

To model the incidence of different injuries or hitting trees during a crash, we would ideally require offsets describing the risk exposure/traffic volume at the point and time of the crash. Such information is impossible to obtain. Other indices for traffic volume, such as vehicle distance traveled, proved to be only indirect measures inadequate for the analysis at specific locations [33]. We avoided this problem by modeling effects on the severity of crashes (or crashes against trees) rather than their occurrence.

Models were adjusted for factors that increase the risk of traffic crashes and may confound an association with street tree canopy. These were initially nine variables, with the list being narrowed down to six for the final modeling. The final six were:

Alignment of the road originally had three categories: straight, curved and unknown, but one crash with unknown alignment was added to the straight category.

Surface condition, originally with four categories: dry (86.5%), wet (13.1%), snow or ice (0.03%), and unknown/not stated (0.3%) was used with only dry and wet/other categories, the latter combined the last three categories except dry.

Weather, originally with seven categories, was used only with fine (84.6%) and rain-overcast-other categories, combining in the latter raining (9.2%), overcast (5.2), other (0.1%), unknown (0.7%), fog/mist (0.2%), and snowing (0.02%). Eventually, the variable was not included into the final modeling due to high correlation (Spearman's rank correlation coefficient, $r_s = 0.77$) with surface conditions.

The *Speed limit* variable had 11 categories for speed from 10 to 110 km/h with a 10 km/h step and an unknown category. For the final modeling, a five-category variable was created. Four crashes with unknown speed limits were added to 60 km/h, the most frequent category; 58 crashes from 10–30 km/h were joined with 40 km/h, and 887 crashes from 90 to 110 km/h were joined with 3003 crashes from 80 km/h category. This variable was used as such to create speed limit subsets for modeling.

Type of location variable had originally 13 categories, seven of which with the smallest size of 1.8% was joined as other. However, for the final modeling another two categories—roundabout (5.5%) and dual freeway (3.0%)—were added to other, due to lack of the outcome event of interest.

Speeding, fatigue, and alcohol were three variables related to human behavior that contributed to crashes. Additionally, a combined *behavioral count* variable was derived by summing up counts for each of the indices, which were assigned a value of 1 if there was involvement in a crash and 0 if not or unknown. Speeding and fatigue variables had two categories related to involvement in a crash: no/unknown and yes, while alcohol had three: unknown, no, and yes. The behavioral count had values 0, 1, 2, and 3. Alcohol and behavioral count were dropped from the final modeling due to the following. Raw frequencies for injuries related to alcohol indicated that they were higher in the no and yes categories relative to the unknown but also higher in the no category relative to the yes category. Speeding and fatigue had more injuries in the yes category relative to no/unknown; however, in the preliminary modeling with co-variates, speeding was associated with an increase in injuries, while fatigue decreased. It was deemed inappropriate to sum them up in a behavioral count variable.

3. Results

3.1. Raw Frequencies of Injuries/Crashes per Category of Variables

Descriptive statistics of the study sample and key variables are reported in Table 1. The cross-tabulation of the variables used for the final modeling are given in Table 2 and Figure 1, while the table with full list of variables is in Supplementary Table S2.

Injuries. Contrary to expectations, different types of injuries were related to street tree percentage in different ways. Crashes that have fatality were not significantly associated with street tree percentage, though there is some increase in cases for areas with street tree percentage of 30% and above. However, the absolute number of cases is very small.

Table 1. Raw frequencies of variables in the study.

Variable/Categories	N	%	Name/Categories	N	%
Sources for outputs variables					
Degree of crash (detailed)			Hits (1st or 2nd) of objects		
Non-casualty (tow-away)	17,214	29.9	None	49,895	86.8
Minor/Other Injury	14,645	25.5	Tree/bus	1320	2.3
Moderate Injury	14,422	25.1	Other	6262	10.9
Serious Injury	10,805	18.8			
Fatal	391	0.7			
Percentage of Street tree percentage categorical variables					
Street tree percentage (%, with regular interval)			Street tree percentage (5, irregular area intervals)		
0–4.9	35,776	62.2	0–4.9	35,776	62.2
5–9.9	6677	11.6	5–9.9	6677	11.6
10–14.9	4404	7.7	10–19.9	7285	12.7
15–19.9	2881	5.0	20–34.9	4482	7.8
20–24.9	2077	3.6	35+	3257	5.7
25–29.9	1408	2.4			
30–34.9	997	1.7			
35–39.9	813	1.4			
40–44.9	602	1.0			
45+	1842	3.2			
Covariates					
Alignment			Surface condition		
Straight	50,572	88.0	Dry	49,729	86.5
Curved	6905	12.0	Wet/other	7748	13.5
Weather					
Fine	48,617	84.6			
Rain/overcast/other	8860	15.4			
Speed limit			Type of location		
10–40 km/h	2963	5.2	T-junction	17,697	30.8
50 km/h	21,440	37.3	2-way undivided	14,855	25.8
60 km/h	21,820	38.0	X-intersection	11,801	20.5
70 km/h	7364	12.8	Divided road	7261	12.6
80–110 km/h	3890	6.8	Other	5863	10.2
Behavioural covariates					
Speeding			Fatigue		
No/unknown	52,424	91.2	No/unknown	54,205	94.3
Yes	5053	8.8	Yes	3272	5.7
Alcohol			Behavioural count		
Unknown	39,986	69.6	0	48,722	84.8
No	15,207	26.5	1	7027	12.2
Yes	2284	4.0	2	1602	2.8
			3	126	0.2

Table 2. Distribution of injuries and hits over categorical variables of study.

Variable/Category	N Total	Injuries (The Severest Injury Type in Crash)												Hits of Objects			
		Fatal		Serious		Moderate		Minor		Fatal/Serious		Fatal/All Injuries		Hits Tree/Bush		Hit Other	
		N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Total	57,477	391	0.68	10,805	18.8	14,422	25.1	14,645	25.5	11,196	19.5	40,263	70.1	1320	2.3	6262	10.9
Street tree percentage variable																	
Street tree percentage (%, regular intervals)																	
0–4.9	35,776	239	0.67	6518	18.2	9093	25.4	9554	26.7	6757	18.9	25,404	71.0	533	1.5	3687	10.3
5–9.9	6677	40	0.60	1252	18.8	1732	25.9	1640	24.6	1292	19.4	4664	69.9	150	2.3	738	11.1
10–14.9	4404	32	0.73	906	20.6	1048	23.8	1065	24.2	938	21.3	3051	69.3	112	2.5	518	11.8
15–19.9	2881	18	0.62	575	20.0	704	24.4	693	24.1	593	20.6	1990	69.1	119	4.1	325	11.3
20–24.9	2077	20	0.96	379	18.3	487	23.5	468	22.5	399	19.2	1354	65.2	81	3.9	251	12.1
25–29.9	1408	6	0.43	277	19.7	353	25.1	333	23.7	283	20.1	969	68.8	52	3.7	174	12.4
30–34.9	997	2	0.20	190	19.1	236	23.7	246	24.7	192	19.3	674	67.6	46	4.6	129	12.9
35–39.9	813	7	0.86	184	22.6	199	24.5	170	20.9	191	23.5	560	68.9	49	6.0	104	12.8
40–44.9	602	6	1.00	127	21.1	126	20.9	125	20.8	133	22.1	384	63.8	40	6.6	86	14.3
45+	1842	21	1.14	397	21.6	444	24.1	351	19.1	418	22.7	1213	65.9	138	7.5	250	13.6
Chi-square (*p*-value)		15.2		39.7	≤0.001	19.9	≤0.05	106.6	≤0.001	43.2	≤0.001	72.8	≤0.001	531	≤0.001	51	≤0.001
Co-variates																	
Alignment																	
Straight	50,572	307	0.61	9294	18.4	12,785	25.3	13,207	26.1	9601	19.0	35,593	70.4	925	1.8	4838	9.6
Curved	6905	84	1.22	1511	21.9	1637	23.7	1438	20.8	1595	23.1	4670	67.6	395	5.7	1424	20.6
Chi-square (*p*-value)		33.4	≤0.001	49	≤0.001	8	≤0.01	90	≤0.001	66	≤0.001	22	≤0.001	410	≤0.001	765	≤0.001
Surface condition																	
Dry	49,729	348	0.70	9428	19.0	12,566	25.3	12,913	26.0	9776	19.7	35,255	70.9	1042	2.1	5008	10.1
Wet/other	7748	43	0.55	1377	17.8	1856	24.0	1732	22.4	1420	18.3	5008	64.6	278	3.6	1254	16.2
Chi-square (*p*-value)		2.1		6	≤0.05	6	≤0.05	46	≤0.001	8	≤0.01	125	≤0.001	67	≤0.001	258	≤0.001
Speed limit																	
10–40 km/h	2963	23	0.78	592	20.0	825	27.8	832	28.1	615	20.8	2272	76.7	34	1.2	174	5.9
50 km/h	21,440	135	0.63	4152	19.4	5302	24.7	4654	21.7	4287	20.0	14,243	66.4	711	3.3	2580	12.0
60 km/h	21,820	148	0.68	4124	18.9	5628	25.8	5884	27.0	4272	19.6	15,784	72.3	387	1.8	2174	10.0
70 km/h	7364	46	0.62	1254	17.0	1771	24.1	2228	30.3	1300	17.7	5299	72.0	105	1.4	764	10.4
80–110 km/h	3890	39	1.00	683	17.6	896	23.0	1047	26.9	722	18.6	2665	68.5	83	2.1	570	14.7
Chi-square (*p*-value)		7.5		26	≤0.001	32	≤0.001	289	≤0.001	25	≤0.001	267	≤0.001	169	≤0.001	184	≤0.001
Type of location																	
T-junction	17,697	102	0.58	3342	18.9	4537	25.6	4727	26.7	3444	19.5	12,708	71.8	275	1.6	1541	8.7
2-way undivided	14,855	128	0.86	3015	20.3	3511	23.6	2813	18.9	3143	21.2	9467	63.7	620	4.2	2031	13.7
X-intersection	11,801	60	0.51	2161	18.3	3203	27.1	3456	29.3	2221	18.8	8880	75.3	74	0.6	731	6.2
Divided road	7261	70	0.96	1309	18.0	1720	23.7	2019	27.8	1379	19.0	5118	70.5	213	2.9	1074	14.8
Other	5863	31	0.53	978	16.7	1451	24.8	1630	27.8	1009	17.2	4090	69.8	138	2.4	885	15.1
Chi-square (*p*-value)		25.9	≤0.001	44	≤0.001	54	≤0.001	477	≤0.001	50	≤0.001	462	≤0.001	437	≤0.001	694	≤0.001
Behavioral co-variates																	
Speeding																	
No/unknown	52,424	275	0.52	9461	18.1	13,178	25.1	14,207	27.1	9736	18.6	37,121	70.8	803	1.5	4252	8.1
Yes	5053	116	2.30	1344	26.6	1244	24.6	438	8.7	1460	28.9	3142	62.2	517	10.2	2010	39.8
Chi-square (*p*-value)		214	≤0.001	221	≤0.001	1		825	≤0.001	313	≤0.001	164	≤0.001	1555	≤0.001	4761	≤0.001
Fatigue																	
No/unknown	54,205	373	0.69	10,083	18.6	13,610	25.1	14,434	26.6	10,456	19.3	38,500	71.0	1060	2.0	5300	9.8
Yes	3272	18	0.55	722	22.1	812	24.8	211	6.5	740	22.6	1763	53.9	260	8.0	962	29.4
Chi-square (*p*-value)		0.9		24	≤0.001	0		662	≤0.001	22	≤0.001	432	≤0.001	494	≤0.001	1224	≤0.001

The number of serious injuries is the only type of injuries that can be claimed, increases slightly with an increase in tree canopy percentage. Moderate injuries decreased slightly, while minor injuries decreased substantially (from 26.7% to 19.1%). Such diverse results prompted us to investigate jointly fatal/serious injuries, which increased from 18.9% to 22.7%, and all injuries, including fatal, which decreased from 71.0% to 65.9%. As can be seen in Figure 1, there are two peaks in fatal/series injuries, around 10–20% and above 30% of street trees percentage, while there are two troughs at these intervals in all injuries attributed to moderate and minor injuries. Yet, linear relationships look like a good approximation.

Crashes. As expected, the percentage of hitting trees/bushes increased with an increase in street trees percentage (from 1.5% to 7.5%). The same occurred to other types of hit objects (e.g., signposts), from 10.3 to 13.6%.

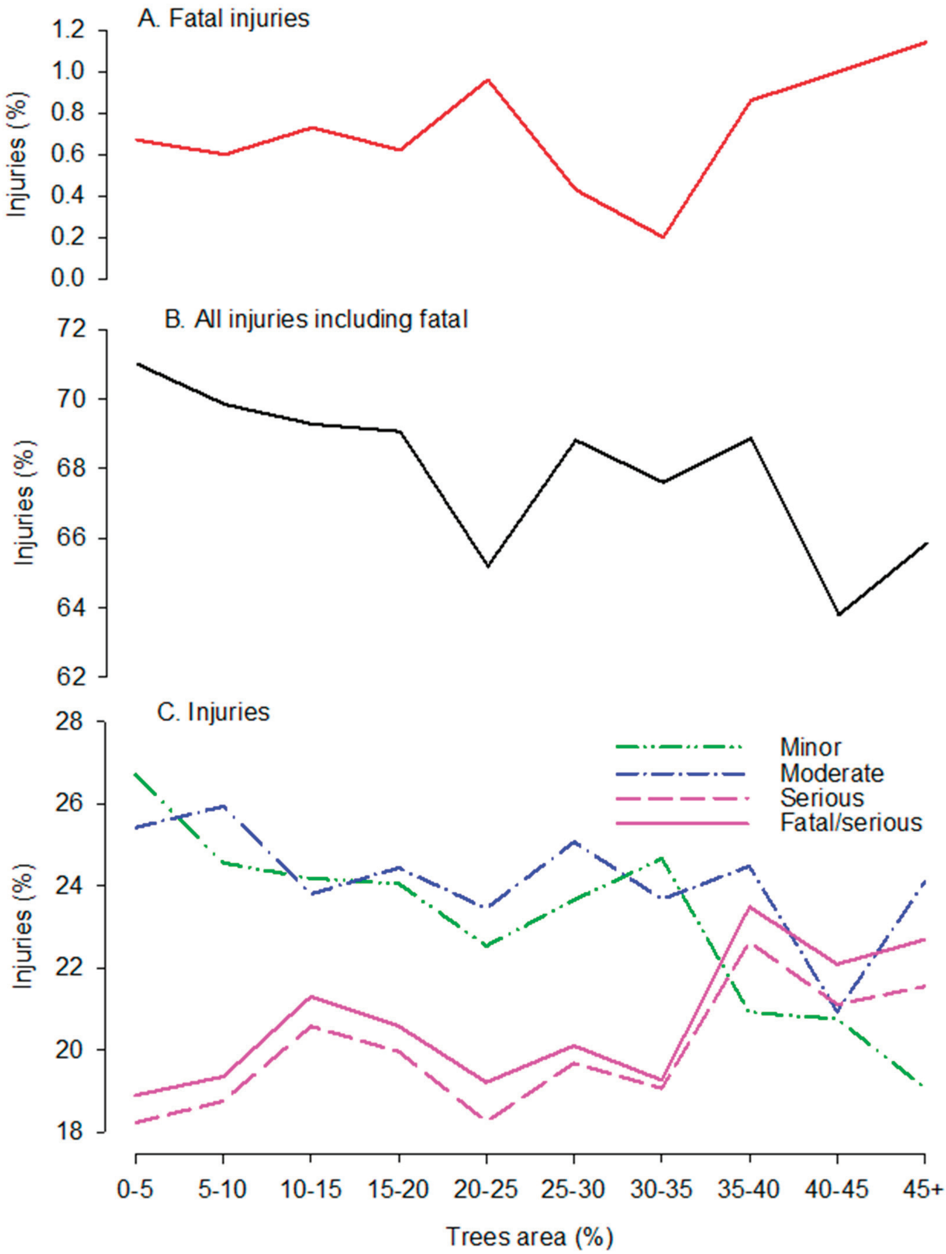

Figure 1. Cross-tabulation of injuries by tree area. The boundaries of the intervals are from equal left boundary to less the right boundary, except 45+, where the right boundary is less/equal to 100.

3.2. Co-Variates and Injuries/Crashes

The details of all injury types and crashes across variables included in the final modeling are in Table 2 and Figure 2. Effects for all described variables are in Supplementary Table S2.

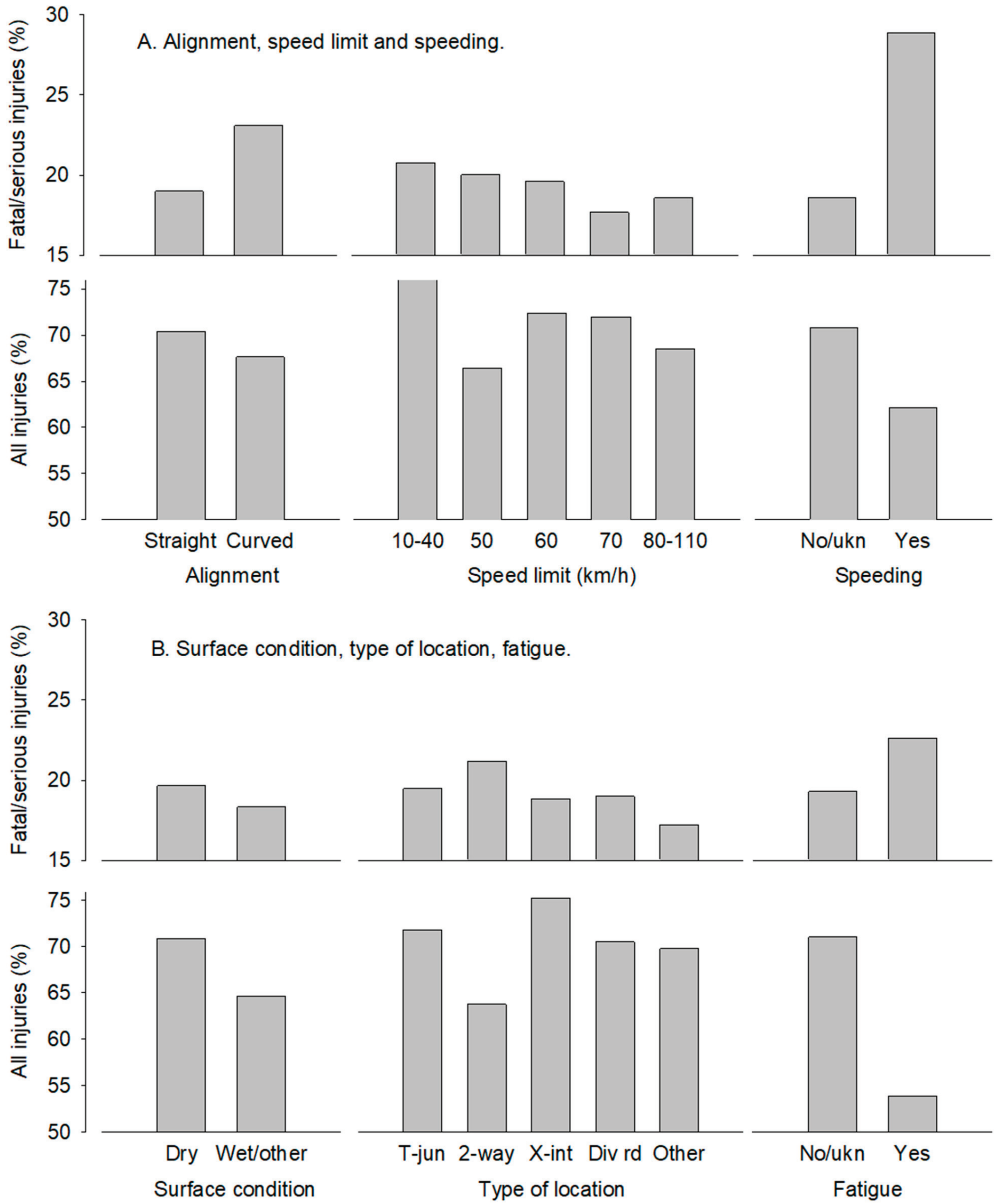

Figure 2. Percentage of fatal/serious injuries (panels in odd rows) and all injuries (panels in even rows) associated with co-variates: raw frequencies. All results are statistically significant by chi-square criterion ($p \leq 0.001$). Type of location categories are: T-junction, 2-way undivided road, X-intersection, divided road, and others. No/unk is No/unknown.

Alignment. Curved vs. straight road is associated with more fatal and serious injuries (23.1% vs. 19.0%) but fewer total injuries (67.6% vs. 70.4%).

Surface condition. In both types of injuries, wet/other conditions are associated with a smaller percentage of injuries than dry: 18.3% vs. 19.7% and 64.6% vs. 70.9% for fatal/serious and all injuries, respectively.

Speed limit. Decline in crashes was related to speed limit, 20.8% to 18.6%, 76.7% to 68.5% associated with minimal and maximal speed limit for fatal/serious and all injuries, respectively.

Type of location. Of the four named locations, ignoring 'other', the minimal fatal and serious injuries are associated with a divided road, while the maximum is with the two-way undivided road (19.0% and 21.2%). The minimal and maximal percentage of all injuries were on two-way undivided road and X-intersection (63.7% and 75.3%), respectively.

Speeding and fatigue. The raw effects are similar, higher percentage of crashes with fatal and serious injuries, but lower percentage of crashes with all injuries. For speeding, fatal and serious injuries where this behavior is involved was 28.9% vs. 18.6% where it was not; while for fatigue, percentages were 22.6% vs. 19.3%, respectively. For all injuries, the related percentages were 62.2% vs. 70.8% and 53.9% vs. 71.0%.

Crashes of objects. Both crashes against trees/bush and other objects increased from 1.5 to 7.5% and 10.3 to 13.6%, respectively, given for the lowest and highest street tree percentage (0–5% and 45% and above).

3.3. Modeling: Exploratory Analysis 1

The details of the analysis are presented fully in Supplementary Tables S3 and S4.

The analysis was based on logistic regression models to estimate the odds of fatal and serious injuries in association with street tree percentage.

The first part of the analysis dealt with a comparison of unadjusted model fits using three types of street tree percentage variables: (1) continuous with a unit of 10%, and two sets of categorical variables with (2) 10 and (3) five categories (Table S3). All three models indicated higher odds of fatal and serious injuries associated with a higher street tree percentage. For both categorical models, the odds ratio with 10–20% and ≥35% street tree percentage were statistically significant.

The second part of the analysis tested the performance of different co-variates in addition to the continuous street trees percentage variable (Table S4). The focus on the continuous street tree percentage variable here was selected due to similar unadjusted results with the more complex categorical versions. Model 1 contained only the street tree percentage variable; Model 2 added alcohol (transformed to have two categories, no/unknown and yes), speeding, and fatigue variables; Model 3 had additional surface condition, weather, speed limit, and type of location; Model 4 was like Model 3 but without alcohol, speeding and fatigue variables. All odds ratios (OR) were consistent and statistically significant across the models.

The odds ratio for street tree percentage (for a 10% increase in the three areas) was slightly attenuated with the addition of co-variates, from OR = 1.04 (Model 1) to 1.03 (Model 2–4). Behavioral variables in Models 2 and 3 returned consistent, statistically significant, but also mixed results. Counterintuitively, the presence of alcohol was associated with lower odds of fatal/serious injuries (OR = 0.88–0.87), whereas these odds were raised among those who were speeding (OR = 1.78–1.80) or reporting fatigue (OR = 1.19–1.17).

Surface conditions being wet or other reduced the odds of fatal/serious injuries (OR = 0.83, 086 for Models 3 and 4), though there was no statistically significant association with weather being rain/other in the same model. Henceforth, the weather was omitted from the model in favor of the surface variable. A speed limit of 70 km/h was the only speed that yielded a statistically significant odds ratio, with lower odds of fatal/serious injuries compared to roads with a speed limit of 10–40 km/h (OR = 0.87–0.86). Type of location categories with reference to T-junction increased the odds of fatal/serious injuries in Model 4 for 2-way undivided road, whereas reduced odds were observed for roundabouts and dual freeways in both Model 3 and 4 (OR = 0.79–0.79 and 0.80–0.81, respectively).

3.4. Modeling: Exploratory Analysis 2

Further exploratory analysis focussed on stratified samples denoted by road speeds of 10–40, 50–70 and 80–110 km/h. Logistic regression models analysed fatal and serious injuries as the outcome variable and the continuous street tree percentage variable with 10%-area unit-increment. The details of the analysis are presented fully in Supplementary Tables S5 and S6.

There were seven models fitted for each subset. Model 1 examined the odds of serious/fatal injuries in association with street tree percentage within each road speed subset. Model 2 was as Model 1 + the location type. Model 3 was as Model 2 + surface condition. Models 4 to 6 were based on Model 3 plus one behavioral variable each (speeding, fatigue, alcohol). Model 7 assessed cumulative behaviors.

The odds ratios for a 10% increase in street tree percentage for all 21 models are in Table S5. The 10–40 km/h subset indicated no association between street tree percentage and the odds of serious/fatal injuries at all, before and after adjusting for confounders. For roads with speed limits of 50–70 kph, a 10% increase in street tree percentage was associated with a 4% increase in the odds of serious/fatal injury. This was attenuated down to 3% but remained statistically significant after adjusting for various confounding variables. Similar was found for roads with speed limits of 80–110 kph, with a 10% increase in street tree percentage associated with an 11% increase in the odds of serious/fatal injuries in the unadjusted model. After adjusting for confounders, the association was attenuated to 6% and remained statistically significant in most models, except for models 4 and 7, which adjusted for speeding.

Table S6 presents all models fully. The subset with low-speed limits, 10–40 km/h, had significant odds ratios only in behavioral variables, i.e., increased odds of serious/fatal injury in the presence of speeding and cumulative behaviors, but also, counterintuitively, lower odds associated with fatigue.

In the subset 50–70 km/h, the following observations were made: increased odds of serious/fatal injury were associated with 2-way undivided roads relative to T-junctions, whereas lower odds were noted for roundabouts and dual freeways. Wet surface conditions were consistently associated with reduced odds of serious/fatal injuries across these models. In contrast with the results for 10–40 km/h, increased odds of serious/fatal injury occurred where speeding or fatigue was reported, while increased odds were also noted where alcohol was present, though this was not statistically significant.

In the subset 80–110 km/h, there was a substantially stronger increase in the odds of serious/fatal injury for crashes at 2-way undivided roads compared with T-junctions and also reduced odds for X-intersections. There were no differences in the odds of serious/fatal injury with respect to surface conditions. The odds of serious/fatal injury were substantially higher within the presence of speeding or fatigue, while alcohol was also associated with higher odds but was not statistically significant.

3.5. Modeling: Final Analysis

There were 84 models in the final analysis. They were applied to a full set and five subsets associated with the following speed limits: 10–40, 50, 60, 70, 80–110 km/h. As a result of both the raw frequencies and exploratory analyses, we decided to omit the alcohol variable (and, consequently, the behavioral count variable) from the co-variate list. Speeding and fatigue were examined separately instead of cumulatively. Given the exploratory evidence of potentially increased risk of serious/fatal injury with respect to higher levels of street tree percentage along roads with higher speed limits, we examined this in more detail by interrogating more speed limit subsets, namely, 50, 60, and 70 km/h, while combining types of location (roundabout, dual freeway, others) into a single category due to similar results from individually small cell counts. In addition to examining fatal and serious injuries as the primary outcome, the final analyses also examined secondary outcome variables, including fatal injuries only, all injuries, and crashes specifically involving collisions with trees/bushes.

The first set of 24 models was fitted with only an intercept and the continuous street tree percentage. A second set of 24 models was adjusted for all covariates (type of location, surface condition, speeding, and fatigue), except for speed limit, because subsets were already partitioned by this variable.

A third set of 24 models was also fitted with all-covariates on the same subsets by the speed limit, but this time with the 5-category street tree percentage variable. These models were used to check if risks of different severities of injury were consistently associated with street tree percentage, or if peaks noted in raw frequencies at 10–20% and ≥35% that were present in covariate-adjusted analyses (Table 2 and Figure 1). The last set consisted of 12 models, and these were fitted on the full sample of crashes combining all four outcomes, with all covariates including speed limit and testing continuous, as well as two categorical street tree percentage variables.

3.6. A. Street Tree Percentage Variables

A summary of the first, second and third set of models is given in Table 3 and Figure 3 (for second set only) presents the odds ratios for each outcomes variable and a 10% increase in street tree percentage. Table 4 supplies the raw frequencies of injuries/crashes per 5-category street tree percentage variable per subsets, to inform model presentations. The fourth set of models are presented in Table S9 (fully) and Figure 4.

Table 3. Final modeling: Association of the incidence of injuries and hits in crashes with a 10% increase in Street tree percentage using logistic regression.

Output Variables	**Full Set and Subsets by Speed Limits**					
	Full set n = 57,477	10–40 km/h n = 2963	50 km/h n = 21,440	60 km/h n = 21,820	70 km/h n = 7364	80–110 km/h n = 3890
	Odds ratio (95% credible Interval)					
	A. Continuous Street tree percentage variable (unit = 10%).					
	1 Models with only Street tree percentage as co-variate (without other co-variates)					
Fatal injuries	1.05 (0.98, 1.12)	0.85 (0.58, 1.16)	0.99 (0.89, 1.10)	1.03 (0.90, 1.17)	1.40 (1.16, 1.65) x	1.21 (1.02, 1.41) +
Fatal and Serious Injuries	1.04 (1.03, 1.06) *	1.00 (0.94, 1.06)	1.02 (0.99, 1.04)	1.05 (1.02, 1.08) x	1.14 (1.07, 1.21) *	1.11 (1.05, 1.17) *
All injuries (including Fatal)	0.95 (0.94, 0.96) *	0.94 (0.89, 0.99) +	0.96 (0.94, 0.97) *	0.97 (0.95, 1.00) +	1.01 (0.95, 1.07)	1.03 (0.98, 1.09)
Hit 1st/2nd of tree/bush	1.33 (1.29, 1.36) *	1.23 (1.05, 1.42) +	1.23 (1.19, 1.27) *	1.42 (1.35, 1.49) *	1.55 (1.38, 1.73) *	1.31 (1.19, 1.45) *
	2 Models with co-variates (without speed limit)					
Fatal injuries	1.00 (0.93, 1.07)	0.85 (0.57, 1.17)	0.96 (0.86, 1.07)	0.94 (0.81, 1.08)	1.25 (1.01, 1.53) +	1.04 (0.86, 1.24)
Fatal and Serious Injuries	1.03 (1.01, 1.04) *	0.99 (0.93, 1.05)	1.02 (0.99, 1.04)	1.02 (0.99, 1.05)	1.08 (1.01, 1.15) +	1.04 (0.98, 1.10)
All injuries (including Fatal)	1.00 (0.98, 1.01)	0.97 (0.92, 1.03)	0.99 (0.98, 1.01)	1.01 (0.98, 1.03)	1.05 (0.99, 1.12)	1.04 (0.99, 1.10)
Hit 1st/2nd of tree/bush	1.20 (1.17, 1.24) *	1.14 (0.96, 1.34)	1.19 (1.14, 1.23) *	1.23 (1.17, 1.30) *	1.24 (1.09, 1.41) x	1.13 (0.99, 1.28)
	3. Five-category Street tree percentage variable (ref = 0–4.9%)					
	Fatal injuries					
5–9.9	0.86 (0.60, 1.20)	0.91 (0.20, 3.03)	0.59 (0.31, 1.05)	1.00 (0.59, 1.61)	0.40 (0.06, 1.58)	1.84 (0.58, 5.22)
10–19.9	0.94 (0.67, 1.26)	0.51 (0.07, 2.12)	0.80 (0.47, 1.31)	0.85 (0.49, 1.45)	1.64 (0.66, 3.58)	1.31 (0.40, 3.61)
20–34.9	0.78 (0.52, 1.16)	0.27 (0.01, 1.92)	0.77 (0.41, 1.37)	0.62 (0.27, 1.27)	1.64 (0.48, 4.78)	0.51 (0.08, 2.18)
35+	1.20 (0.81, 1.74)	0.32 (0.01, 2.34)	0.95 (0.52, 1.63)	0.93 (0.38, 2.02)	3.41 (0.92, 10.20)	1.95 (0.67, 5.26)
	Fatal and Serious Injuries					
5–9.9	1.02 (0.96, 1.09)	0.87 (0.64, 1.17)	0.95 (0.86, 1.06)	1.10 (0.99, 1.23)	0.95 (0.77, 1.17)	1.09 (0.79, 1.48)
10–19.9	1.12 (1.05, 1.19) *	0.96 (0.71, 1.30)	1.08 (0.98, 1.19)	1.14 (1.02, 1.27) +	1.13 (0.92, 1.37)	1.17 (0.89, 1.52)
20–34.9	1.00 (0.92, 1.08)	0.91 (0.66, 1.28)	0.89 (0.79, 1.00)	1.08 (0.94, 1.23)	1.24 (0.92, 1.65)	0.95 (0.69, 1.29)
35+	1.17 (1.07, 1.28) *	0.99 (0.69, 1.39)	1.17 (1.04, 1.32) x	1.01 (0.84, 1.23)	1.40 (0.92, 2.09)	1.36 (0.96, 1.90)
	All injuries (including Fatal)					
5–9.9	1.00 (0.94, 1.06)	1.02 (0.77, 1.36)	0.95 (0.87, 1.04)	1.03 (0.94, 1.14)	1.09 (0.91, 1.30)	1.06 (0.82, 1.36)
10–19.9	0.99 (0.94, 1.05)	0.98 (0.74, 1.30)	0.95 (0.87, 1.03)	1.14 (1.03, 1.26) x	0.93 (0.78, 1.10)	0.91 (0.74, 1.14)
20–34.9	0.94 (0.88, 1.01)	0.95 (0.71, 1.31)	0.88 (0.80, 0.97) x	0.96 (0.85, 1.08)	1.08 (0.83, 1.41)	1.23 (0.94, 1.64)
35+	1.00 (0.92, 1.08)	0.78 (0.56, 1.09)	1.02 (0.92, 1.14)	0.95 (0.81, 1.13)	1.37 (0.92, 2.07)	1.18 (0.86, 1.63)
	Hit 1st or hit 2nd of tree/bush during the crash					
5–9.9	1.32 (1.09, 1.59) x	0.55 (0.09, 2.33)	0.96 (0.73, 1.25)	1.81 (1.55, 2.38) *	2.02 (1.10, 3.59) +	1.34 (0.51, 3.09)
10–19.9	1.78 (1.52, 2.08) *	1.40 (0.43, 3.91)	1.43 (1.14, 1.78) x	2.30 (1.97, 2.77) *	1.55 (0.82, 2.75)	2.45 (1.28, 4.54) x
20–34.9	1.93 (1.61, 2.31) *	2.11 (0.72, 5.58)	1.49 (1.16, 1.90) x	2.15 (1.57, 2.75) *	1.78 (0.87, 3.45)	2.46 (1.18, 4.92) +
35+	2.88 (2.43, 3.44) *	2.28 (0.76, 6.13)	2.53 (2.05, 3.13) *	3.41 (2.50, 4.76) *	2.04 (0.83, 4.61)	2.07 (0.94, 4.41)

Models are logistic regressions for injuries or hits of trees and objects. Percentage of trees variable is continuous; only Street tree percentage is presented. The results for covariates are omitted. * $p \leq 0.001$, x $p \leq 0.01$, + $p \leq 0.05$. MCMC using MLwiN with 3000–20,000 burn-in and sample iterations.

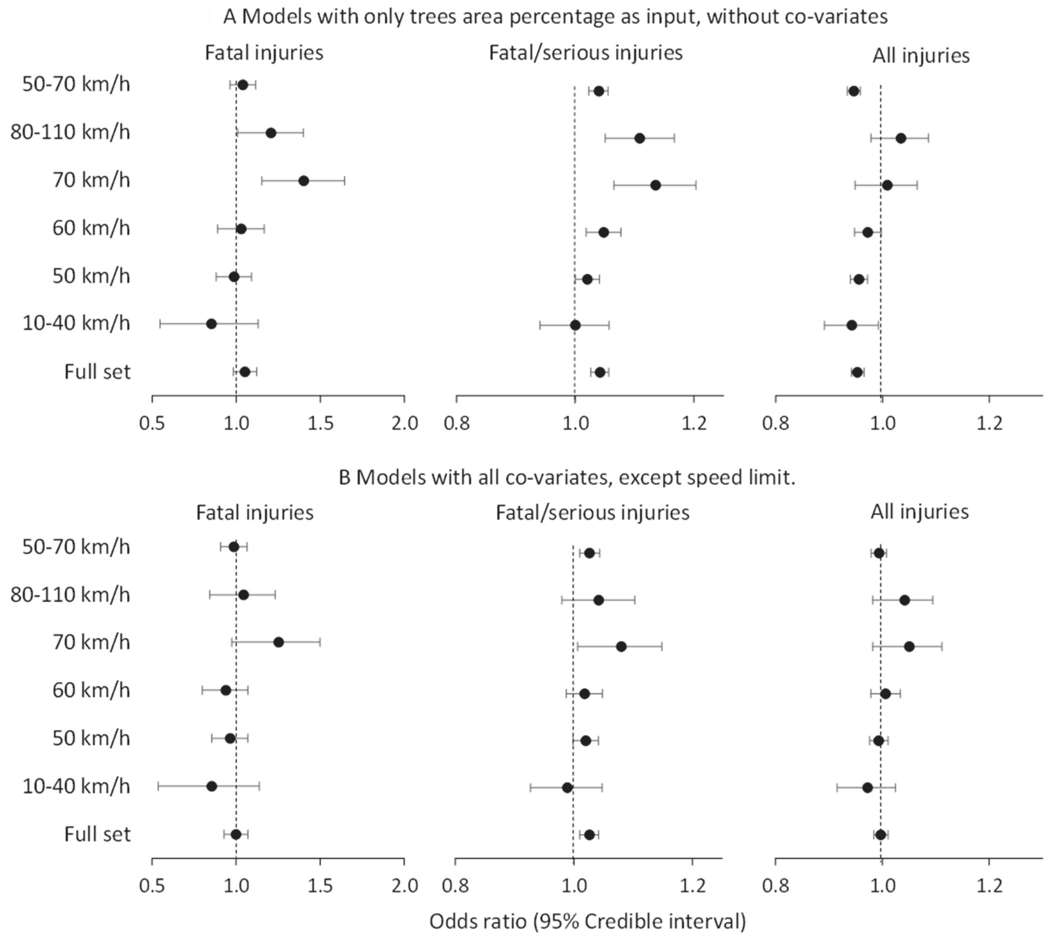

Figure 3. Association of the incidence of injuries with 10% increase in trees area using logistic regression. The percentage of trees variable is continuous. (**A**) Models with only tree area percentage and intercept; (**B**) Models with all co-variates except speed limit. Models are built on a full set and subsets related to different speed limits. MCMC procedure using MLwiN with 3000–20,000 burn-in and sample iterations was used. Note different x-ranges, and additional to the ones described in the text 50–70 km/h subset of data.

A1. Unadjusted models (Models 1, continuous street tree percentage variable, Table 3). As expected, the size of odds ratios here was the largest, as the variation can be attributed to co-variates that were not present (but then adjusted in the second set of models; see A2 below). Associations with fatal injuries were increased significantly for subsets with the following higher speed limits: 70 and 80–110 km/h. The odds of serious/fatal injuries were increased consistently, except in the subset with the slowest speed limit. However, the odds of any injuries were significantly reduced with a 10% increase in street tree percentage in the full sample and in subsets with speed limits up to 60 km/h, while being not statistically significant for crashes on roads with speed limits at 70 km/h or above. Associations of crashes into trees/bushes with street tree percentage were higher in all subsets and the full sample.

Table 4. Raw frequencies of injuries/hits by Street tree percentage per subsets with different speed limits.

		Injuries							
Street tree percentage %	Subsets N total	Fatal N	%	Fatal/Serious N	%	Injuries all N	%	Hitting tree/bush N	%
	Full set								
Total	57,477	391	0.7	11,196	19.5	40,263	70.1	1320	2.3
0–4.9	35,776	239	0.7	6757	18.9	25,404	71.0	533	1.5
5–9.9	6677	40	0.6	1292	19.4	4664	69.9	150	2.3
10–19.9	7285	50	0.7	1531	21.0	5041	69.2	231	3.2
20–34.9	4482	28	0.6	874	19.5	2997	66.9	179	4.0
35 plus	3257	34	1.0	742	22.8	2157	66.2	227	7.0
Chi-square (*p*-value)		7.3		41.7	≤0.001	62.7	≤0.001	503.2	≤0.001
	10–40 km/h								
Total	2963	23	0.8	615	20.8	2272	76.7	34	1.1
0–4.9	1839	16	0.9	387	21.0	1429	77.7	15	0.8
5–9.9	335	3	0.9	63	18.8	259	77.3	2	0.6
10–19.9	315	2	0.6	66	21.0	239	75.9	5	1.6
20–34.9	259	1	0.4	52	20.1	194	74.9	6	2.3
35 plus	215	1	0.5	47	21.9	151	70.2	6	2.8
Chi-square (*p*-value)		1.1		1.1		6.7		11.5	≤0.05
	50 km/h								
Total	21,440	135	0.6	4287	20.0	14,243	66.4	711	3.3
0–4.9	10,948	76	0.7	2175	19.9	7433	67.9	275	2.5
5–9.9	2920	12	0.4	554	19.0	1938	66.4	71	2.4
10–19.9	3360	19	0.6	708	21.1	2205	65.6	123	3.7
20–34.9	2243	13	0.6	406	18.1	1411	62.9	92	4.1
35 plus	1969	15	0.8	444	22.6	1256	63.8	150	7.6
Chi-square (*p*-value)		3.8		17.5	≤0.01	30.1	≤0.001	148.4	≤0.001
	60 km/h								
Total	21,820	148	0.7	4272	19.6	15,784	72.3	387	1.8
0–4.9	14,920	99	0.7	2817	18.9	10,818	72.5	158	1.1
5–9.9	2408	18	0.8	497	20.6	1741	72.3	53	2.2
10–19.9	2413	16	0.7	516	21.4	1786	74.0	70	2.9
20–34.9	1370	8	0.6	290	21.2	955	69.7	56	4.1
35 plus	709	7	1.0	152	21.4	484	68.3	50	7.1
Chi-square (*p*-value)		1.4		15.1	≤0.01	14.2	≤0.01	219.4	≤0.001
	70 km/h								
Total	7364	46	0.6	1300	17.7	5299	72.0	105	1.4
0–4.9	5471	28	0.5	928	17.0	3948	72.2	51	0.9
5–9.9	699	2	0.3	117	16.7	511	73.1	17	2.4
10–19.9	753	8	1.1	150	19.9	520	69.1	17	2.3
20–34.9	304	4	1.3	69	22.7	216	71.1	12	4.0
35 plus	137	4	2.9	36	26.3	104	75.9	8	5.8
Chi-square (*p*-value)		18.7	≤0.001	17.2	≤0.01	4.9		51	≤0.001
	80–110 km/h								
Total	3890	39	1.0	722	18.6	2665	68.5	83	2.1
0–4.9	2598	20	0.8	450	17.3	1776	68.4	34	1.3
5–9.9	315	5	1.6	61	19.4	215	68.3	7	2.2
10–19.9	444	5	1.1	91	20.5	291	65.5	16	3.6
20–34.9	306	2	0.7	57	18.6	221	72.2	13	4.3
35 plus	227	7	3.1	63	27.8	162	71.4	13	5.7
Chi-square (*p*-value)		12.9	≤0.05	16.6	≤0.01	4.7		33.7	≤0.001

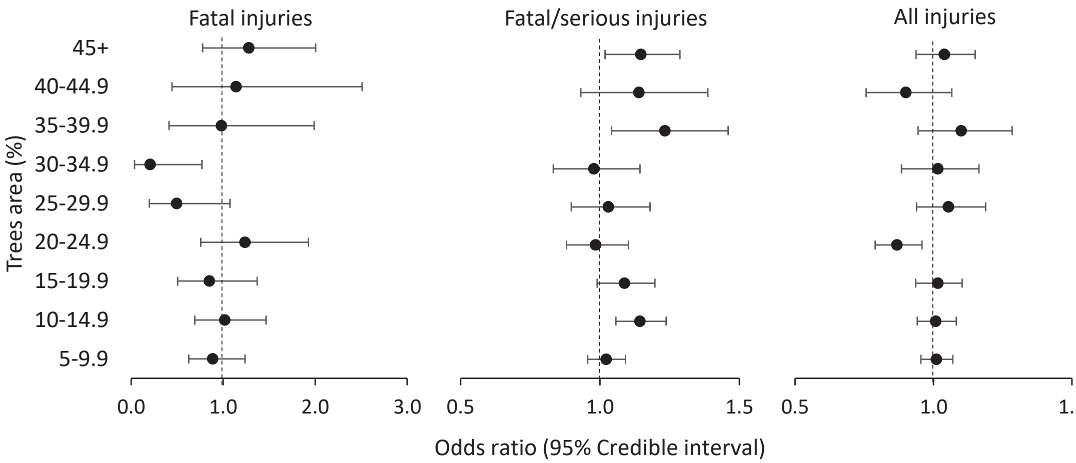

Figure 4. Association of the incidence of injuries with 10-category trees area variable using logistic regression. The reference category is 0–4.9% of the tree area. Models built on the full set, with all co-variates, including speed limit speed limits. MCMC procedure using MLwiN with 3000–20,000 burn-in and sample iterations was used. Note different x-ranges.

A2. Models adjusted for co-variates (Models 2, continuous street tree percentage variable, Table 3). The number of significant odds ratios for injuries dropped substantially. Only the 70-km/h subset had fatal injuries statistically significantly associated with street tree percentage. However, this needs to be taken carefully, as the total number of fatalities in this subset was only n = 46, and only n = 8 of them occurred where street tree percentage ≥20% (see Table 4). Serious/fatal injuries were associated with street tree percentage in the full sample (OR 1.03), 50-km/h (OR 1.02), and 70-km/h (OR 1.08) subsets.

There were no statistically significant associations for all injury outcomes. Associations of crashes into trees/bushes with street tree percentage were increased in all sample subsets but less so than in unadjusted models. The peak danger was associated with street tree percentage, and crashes into trees/bushes were observed for roads at a speed limit of 70 km/h.

A3. Models with co-variates without speed limits (Models 3, 5-category street tree percentage variable, Table 3). Co-variate adjusted models yielded broadly similar results to those unadjusted. Associations between street tree canopy and fatal injuries were entirely absent of statistical significance (i.e., no clear evidence of higher or lower odds of fatal injury with higher street tree percentage along roads of any speed limit). For serious/fatal injuries along roads of any speed, there were higher odds where street tree percentage was 10–20% or 20–35% compared with 0–4.9%. Along roads of 50 km/h, higher odds were reported only where the street tree percentage was ≥35%. Along roads of 60 km/h, higher odds of serious/fatal injury were observed only where street tree canopy was 10–19.9%, but not where tree canopy was greater. No statistically significant odds ratios were reported for street tree percentage along roads with speed limits ≥70 km/h. The odds of any injury occurring were higher only along roads of 60 km/h where street tree percentage was 10–19.9% (but not higher) in comparison with 0–4.9%. Injury odds were actually lower, with a street tree percentage of 20–34.9% along roads of 50 km/h, with no other statistically significant associations. Odds of crashes involving trees/bushes were almost uniformly increased along roads of any speed where there were higher percentages of street trees present. Raw frequencies of injuries and crashes are in Table 4.

A4. Models with all co-variates, including speed limits, using three street tree percentage variables built on a full set (Table S9 and Figure 4). Analyses of the continuous street tree percentage variable have shown similar associations as those models with only stratification (but not adjustment) for speed limits. In particular, the association with serious/fatal injuries was statistically significant (OR = 1.03, 1.01–1.04) and crashes involving trees/bushes (OR = 1.20, 1.17–1.24). Analysis of street tree percentage in 10 strata provided further support. There were lower odds of fatal injury for street tree percentage of 25–35%, increased odds of fatal and serious injuries in 10–20% and ≥35% street tree percentage, and lower odds of all injuries for street tree percentage 20–25%. Odds of crashes were increased in all categories relative to the reference street tree percentage of 0–5%. Models with the five-category street tree percentage variable showed similar associations for the odds of serious/fatal injuries and crashes involving trees/bushes and no associations for the fatal and all injury outcome variables.

4. Discussion

The key findings from our assessment of associations between street tree percentage, injury, and death from a large sample of traffic crashes in Australia's biggest city are as follows. First, running counter to our first hypothesis, a 10% increase in street trees was associated with a 3% increase in the odds of serious/fatal injuries on roads of any speed limit (OR = 1.03, 95%CI = 1.01–1.04) after adjustment for behavioral and structural confounders. Second, the odds of any injury occurring or death separate from serious injury were not associated with a 10% increase in street trees (positively or negatively). Seemingly protective effects observed in unadjusted models for all injuries were explained by adjustment for confounding. Third, when considering roads with different speed limits, a 10% increase in street tree percentage was statistically significantly associated with an 8% (OR = 1.08, 95%CI = 1.01–1.15) increase in the odds of serious/fatal injury and 25% (OR = 1.25, 95%CI = 1.01–1.53) increased odds of death along roads of ≥70 km/h. Fourth, we did not observe any similar associations between street tree percentage and any of the injury/death outcomes for roads with speeds less than 70 km/h. In combination, these results support our supposition that association size between street trees and injury or death from traffic accidents is contingent upon road speed. It does not, however, appear to be the case that street trees confer any protective effect; rather, there is no increased risk of harm from their presence along roads with speed limits less than 70km/h.

The absence of association between serious or fatal traffic accidents and the percentage of street trees along roads with speed limits lower than 70 km/h indicates that speed is the key determinant, rather than street trees promoting more careful driving [17,18] or promoting psychological restorative processes that ameliorate the stress of driving [11]. Our research also confirms results from previous work on the increased risks of fatal or serious injuries in crashes where speeding [13] or fatigue [14,15] were reported. Wet surface conditions were associated with reduced odds of fatal or serious injuries, unlike previous evidence [12]. This may be due to a selection effect wherein some people may be less likely to drive in precarious weather conditions, and others may be more vigilant than normal. Unlike some previous work [16], we found the presence of alcohol was associated with lower risks of fatal or serious injuries. Some work with similar results speculate that intoxication may mean drivers are more relaxed at the time of a crash and relatively less likely to sustain an injury as a result, compared to sober drivers or passengers who tend to tense up, but the evidence is mixed and not strong enough to draw any firm conclusions [34–36].

The strengths of this study include the large sample size and the full data on crashes occurring across the entire jurisdiction of metropolitan Sydney, a city of over 5 million people with diverse topography and variable infrastructure quality encompassing higher-density inner city areas and vast urban sprawl. Data available permitted control of a wide range of behavioral and structural sources of confounding. The comprehensiveness of the data also permitted the identification of crashes that actually involved collisions into trees. It is important to emphasize that the majority of crashes (97%) did not. It was no surprise that the analyses of collisions with trees did indicate consistently greater odds of occurrence along roads where there is more street tree coverage. Unfortunately, data were not available to distinguish between collisions that occurred because of a tree that had fallen into the road in front of an oncoming vehicle and collisions that resulted from an errant vehicle veering off-road. The former might be addressed by urban foresters through monitoring and preventive measures, whereas the latter is a problem with errant vehicles. A related limitation is that no data were available on how many pedestrian lives were saved because they were shielded by trees into which vehicles collided. Thus, the analysis is skewed towards measuring the harms side of the ledger, with prevention unmeasured.

Finally, there are incidents reported of street trees being felled for purposes of road expansion and due to malicious actions of rogue individuals attempting to boost housing prices by revealing green or sea vistas. While data to which we had access did not permit examination of change in tree canopy cover as a predictor of road traffic accidents, neither is likely to substantially affect the overall results as the former usually occurs during protracted periods of road closure, and the latter tends to skew towards minor roads through coastal areas. Nevertheless, the assessment of change in canopy cover as a result of street tree planting and trajectories, not only in road traffic accidents but also potential increases in walking and cycling, would be a valuable future avenue for research. Relatedly, our tree data did not permit an ability to distinguish between different densities of street tree planting, differences in tree species and trunk diameter, locations on footpaths versus encroaching onto roads, or differences between proactive and routine tree pruning versus reactive and proper versus improper pruning; all of these may have localized impacts on visibility that might be important for determining crash risk and injury severity.

5. Conclusions

These results paint a nuanced picture contingent upon speed. There is a small degree of support for public health concerns among transport planners, and this is reserved specifically for street tree provision along roads of 70 km/h and serious/fatal injuries (for every 10% increase in street tree percentage, the odds of serious/fatal injury rose 8% along roads of 70 km/h). However, there was no statistically significant risk for injuries, including those less serious, nor for serious/fatal injuries along roads with speed limits lower than 70 km/h. This gives a strong indication of two potential policy recommendations. Firstly, to prioritize planting and preservation of street tree canopy cover along roads less than 70 km/h, given that a higher level of street tree provision along roads with speed limits less than 70 km/h is not statistically associated with increased risk of death or injury of any severity. Second, consider reducing speed limits on roads currently set at 70 km/h to less than 70 km/h, which our findings indicate may alleviate the risk of serious/fatal injury associated with street tree provision. In combination, these measures may alleviate the residual risk for serious/fatal injuries while maintaining the ecosystem services and mental, physical, and social health benefits of street trees.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land13111815/s1, Table S1. Selection of the best road area threshold for crash data exclusion and correction; Table S2. Distribution of injuries and hits over categorical variables of study; Table S3. Selection of street tree variable; Table S4. Testing models with different complement of co-variates; Table S5. Logistic regression for incidence of crashes with fatal or serious injuries with 10% increase in street tree; Table S6. Logistic regression for incidence of crashes with fatal or serious injuries by three subsets of speed limits: full results; Table S7. Final modelling: Association of the incidence of injuries and hits in crash with continuous street tree and all co-variates in logistic models.; Table S8. Final modelling: Association of the incidence of injuries and hits in crash with all co-variates in logistic models: street tree is 5-category variable.; Table S9. Logistic regression on full set with all covariates including speed limit: different street tree variables.

Author Contributions: Conceptualization, X.F., M.N. and T.A.-B.; methodology, X.F., M.N. and T.A.-B.; software, M.N.; validation, T.A.-B.; formal analysis, M.N.; investigation, X.F., M.N. and T.A.-B.; resources, X.F., M.N. and T.A.-B.; data curation, X.F., M.N. and T.A.-B.; writing—original draft preparation, X.F., M.N. and T.A.-B.; writing—review and editing, X.F., M.N. and T.A.-B.; visualization, M.N.; supervision, X.F. and T.A.-B.; project administration, X.F.; funding acquisition, X.F. and T.A.-B. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge funding from NSW Government. We are grateful for the APC waiver.

Data Availability Statement: Data is confidential.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ma, S.; Pitman, A.; Hart, M.; Evans, J.P.; Haghdadi, N.; MacGill, I. The impact of an urban canopy and anthropogenic heat fluxes on Sydney's climate. *Int. J. Climatol.* **2017**, *37*, 255–270. [CrossRef]
2. Deilami, K.; Kamruzzaman, M.; Liu, Y. Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures. *Int. J. Appl. Earth Obs. Geoinf.* **2018**, *67*, 30–42. [CrossRef]
3. Feng, X.; Toms, R.; Astell-Burt, T. Association between green space, outdoor leisure time and physical activity. *Urban For. Urban Green.* **2021**, *66*, 127349. [CrossRef]
4. Roscoe, C.; Sheridan, C.; Geneshka, M.; Hodgson, S.; Vineis, P.; Gulliver, J.; Fecht, D. Green walkability and physical activity in UK Biobank: A cross-sectional analysis of adults in Greater London. *Int. J. Environ. Res. Public Health* **2022**, *19*, 4247. [CrossRef]
5. Frumkin, H. Urban sprawl and public health. *Public Health Rep.* **2002**, *117*, 201–217. [CrossRef]
6. Rissel, C.E. Active travel: A climate change mitigation strategy with co-benefits for health. *N. South Wales Public Health Bull.* **2009**, *20*, 10–13. [CrossRef]
7. City of Sydney. Greening Sydney Strategy. Available online: https://www.cityofsydney.nsw.gov.au/strategies-action-plans/greening-sydney-strategy (accessed on 12 October 2021).
8. City of Barcelona. Trees for Life: Master Plan for Barcelona's Trees 2017–2037. Available online: https://www.c40knowledgehub.org/s/article/Trees-for-Life-Master-Plan-for-Barcelona-s-Trees-2017-2037?language=en_US (accessed on 13 March 2021).
9. City of Vancouver. Park Board Achieves Target to Plant 150,000 Trees by 2020. Available online: https://vancouver.ca/news-calendar/park-board-achieves-target-to-plant-150000-trees-by-2020.aspx (accessed on 13 March 2021).
10. City of Seattle. Trees For Seattle. Available online: https://www.seattle.gov/trees/management/canopy-cover (accessed on 13 March 2021).
11. Van Treese, J.W., II; Koeser, A.K.; Fitzpatrick, G.E.; Olexa, M.T.; Allen, E.J. A review of the impact of roadway vegetation on drivers' health and well-being and the risks associated with single-vehicle crashes. *Arboric. J.* **2017**, *39*, 179–193. [CrossRef]
12. Theofilatos, A.; Yannis, G. A review of the effect of traffic and weather characteristics on road safety. *Accid. Anal. Prev.* **2014**, *72*, 244–256. [CrossRef]
13. Aarts, L.; Van Schagen, I. Driving speed and the risk of road crashes: A review. *Accid. Anal. Prev.* **2006**, *38*, 215–224. [CrossRef]
14. Zhang, G.; Yau, K.K.; Zhang, X.; Li, Y. Traffic accidents involving fatigue driving and their extent of casualties. *Accid. Anal. Prev.* **2016**, *87*, 34–42. [CrossRef]
15. Moradi, A.; Nazari, S.S.H.; Rahmani, K. Sleepiness and the risk of road traffic accidents: A systematic review and meta-analysis of previous studies. *Transp. Res. Part F Traffic Psychol. Behav.* **2019**, *65*, 620–629. [CrossRef]
16. Glucksman, E. Alcohol and accidents. *Br. Med. Bull.* **1994**, *50*, 76–84. [CrossRef]
17. Ewing, R.; Dumbaugh, E. The built environment and traffic safety: A review of empirical evidence. *J. Plan. Lit.* **2009**, *23*, 347–367. [CrossRef]
18. Calvi, A. Does roadside vegetation affect driving performance? Driving simulator study on the effects of trees on drivers' speed and lateral position. *Transp. Res. Rec.* **2015**, *2518*, 1–8. [CrossRef]
19. Hartig, T.; Mitchell, R.; de Vries, S.; Frumkin, H. Nature and Health. *Annu. Rev. Public Health* **2014**, *35*, 207–228. [CrossRef] [PubMed]
20. Markevych, I.; Schoierer, J.; Hartig, T.; Chudnovsky, A.; Hystad, P.; Dzhambov, A.M.; de Vries, S.; Triguero-Mas, M.; Brauer, M.; Nieuwenhuijsen, M.J.; et al. Exploring pathways linking greenspace to health: Theoretical and methodological guidance. *Environ. Res.* **2017**, *158*, 301–317. [CrossRef]
21. Astell-Burt, T.; Feng, X. Urban green space, tree canopy and prevention of cardiometabolic diseases: A multilevel longitudinal study of 46 786 Australians. *Int. J. Epidemiol.* **2020**, *49*, 926–933. [CrossRef]
22. Astell-Burt, T.; Feng, X. Does sleep grow on trees? A longitudinal study to investigate potential prevention of insufficient sleep with different types of urban green space. *SSM Popul. Health* **2020**, *10*, 100497. [CrossRef]
23. Astell-Burt, T.; Feng, X. Association of Urban Green Space with Mental Health and General Health Among Adults in Australia. *JAMA Netw. Open* **2019**, *2*, e198209. [CrossRef]
24. Feng, X.; Toms, R.; Navakatikyan, M.; Astell-Burt, T. The nexus between urban green space, housing type, and mental health. *Soc. Psychiatry Psychiatr. Epidemiol.* **2022**, *57*, 1917–1923. [CrossRef]
25. Kardan, O.; Gozdyra, P.; Misic, B.; Moola, F.; Palmer, L.J. Neighborhood greenspace and health in a large urban center. *Sci. Rep.* **2015**, *5*, 11610. [CrossRef] [PubMed]
26. Kondo, M.C.; Mueller, N.; Locke, D.H.; Roman, L.A.; Rojas-Rueda, D.; Schinasi, L.H.; Gascon, M.; Nieuwenhuijsen, M.J. Health impact assessment of Philadelphia's 2025 tree canopy cover goals. *Lancet Planet. Health* **2020**, *4*, e149–e157. [CrossRef] [PubMed]

27. Browning, M.H.; Lee, K.; Wolf, K.L. Tree cover shows an inverse relationship with depressive symptoms in elderly residents living in US nursing homes. *Urban For. Urban Green.* **2019**, *41*, 23–32. [CrossRef]
28. Marselle, M.R.; Bowler, D.E.; Watzema, J.; Eichenberg, D.; Kirsten, T.; Bonn, A. Urban street tree biodiversity and antidepressant prescriptions. *Sci. Rep.* **2020**, *10*, 22445. [CrossRef]
29. Giacinto, J.J.; Fricker, G.A.; Ritter, M.; Yost, J.; Doremus, J. Urban forest biodiversity and cardiovascular disease: Potential health benefits from California's street trees. *PLoS ONE* **2021**, *16*, e0254973. [CrossRef]
30. Rasbash, J.; Steele, F.; Browne, W.J.; Goldstein, H. *A User's Guide to MLwiN*; Version 3.05; Centre for Multilevel Modelling, University of Bristol: Bristol, UK, 2020.
31. Browne, W.J. *MCMC Estimation in MLwiN*, v3.03; Centre for Multilevel Modelling, University of Bristol: Bristol, UK, 2019.
32. Steele, F. *Module 6: Regression Models for Binary Responses Concepts*; Centre for Multilevel Modelling, University of Bristol: Bristol, UK, 2009.
33. Harvey, C.; Aultman-Hall, L. *Urban Streetscape Design and Crash Severity*; Transportation Research Board: Washington, DC, USA, 2015; pp. 1–8.
34. Friedman, L.S. Dose–response relationship between in-hospital mortality and alcohol following acute injury. *Alcohol* **2012**, *46*, 769–775. [CrossRef]
35. Hsieh, C.-H.; Su, L.-T.; Wang, Y.-C.; Fu, C.-Y.; Lo, H.-C.; Lin, C.-H. Does alcohol intoxication protect patients from severe injury and reduce hospital mortality? The association of alcohol consumption with the severity of injury and survival in trauma patients. *Am. Surg.* **2013**, *79*, 1289–1294. [CrossRef]
36. Plurad, D. Motor vehicle crashes: The association of alcohol consumption with the type and severity of injuries and outcomes. *J. Emerg. Med.* **2010**, *38*, 12–17. [CrossRef]

MDPI AG
Grosspeteranlage 5
4052 Basel
Switzerland
Tel.: +41 61 683 77 34

Land Editorial Office
E-mail: land@mdpi.com
www.mdpi.com/journal/land

Academic Open
Access Publishing

mdpi.com

ISBN 978-3-7258-3174-6