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Special Issue Reprint

Advances in Urban Green Development and Resilient Cities

Edited by
Marco Devecchi, Fabrizio Aimar and Matteo Caser

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About the Editors

Marco Devecchi

Marco Devecchi graduated in Agricultural Sciences from the Faculty of Agriculture of the University of Turin and holds a Ph.D. in "Landscape Study and Planning".

His scholarly interests focus on floriculture, landscaping, parks, and gardens. As an associated professor, he coordinates the Interuniversity Degree Course in "Progettazione delle aree verdi e del paesaggio" for the Department of Agricultural, Forest and Food Science of the University of Turin. Since 2008, he has been deputy of the University of Turin in the General Assembly of the European Network of Universities for the implementation of the European Landscape Convention (UNISCAPE).

Additionally, Devecchi coordinates a research team of the Department of Agricultural, Forest, and Food Science that carries out research in urban green areas, historic gardens, and rural landscapes. Recently, the group was involved in several research projects on landscape topics, in collaboration with Italian and international universities and research centres. His research activities mainly concern the knowledge, safeguarding, and valorisation of rural landscapes and green technologies. He cooperates on national and international projects.

Devecchi is a member of the "Società Orticola Italiana" and of International Society for Horticultural Science (ISHS). Since May 2003, he has been president of the "Osservatorio del paesaggio per il Monferrato e l'Astigiano". From 1 January 2010 to 1 January 2013, he was the coordinator of the Observatory Network of Landscape of Piedmont. Since 2023, he has been president of the Agricultural Academy of Turin.

He has authored about 140 scientific publications about rural landscapes, floriculture, and historic gardens and also serves as a peer reviewer for international academic journals.

Fabrizio Aimar

Fabrizio Aimar, Architect, Ph.D. with honours in Urban and Regional Development from the Polytechnic University of Turin, Italy, has been an assistant professor of Practice in the Department of Architecture at Texas A&M University, USA. He also directs the Center for Heritage Conservation and holds the Woodcock Endowed Professorship in Historic Preservation. Previously, he served as a lecturer and the department head of Architecture and Civil Engineering at POLIS University, Tirana, Albania (2021–2023).

In 2021, Aimar was on the Advisory Board of the Italian Pavilion at the 17th Architecture Venice Biennale, while in 2023, he participated as a speaker in the collateral event "Students as Researchers" at the 18th Architecture Venice Biennale. Moreover, he was a visiting researcher at ICCROM, Italy and collaborated with the Responsible Risk Resilience Centre at the Polytechnic University of Turin, Italy (2019–2022).

His expertise includes urban resilience, sustainable development, built and cultural heritage, landscape resilience, and cultural landscapes. He has authored numerous peer-reviewed articles, book chapters, and conference proceedings, including the monograph "The Resilience of Cultural Landscapes: Perspectives from UNESCO World Heritage Sites" (Springer, 2024). Aimar has been a scientific committee member for journals such as *archiDOCT* (ISSN 2309-0103, Scopus Index), *Urbanistica* (ISSN 0042-1022), and the *GeoProgress Journal* (ISSN 2384-9398).

Lastly, Aimar was elected to the Executive Board of the Order of Architects, Planners, Landscape Architects, and Conservators of the Province of Asti, Italy (2017–2021), and he previously served on its Culture Commission (2010–2016). He was an invited speaker at the 28th International Book Fair in Turin and the Chamber of Deputies of the Italian Parliament in Rome in 2015.

Matteo Caser

Matteo Caser is an assistant professor at the Department of Agricultural, Forest and Food Sciences of the University of Turin. He holds a Ph.D. in Agricultural, Forestry, and Food Sciences from the University of Turin, entitled "The role of DNA markers in biodiversity analysis and characterization of local ornamental germplasm: genera Camellia, Rhododendron, and Campanula".

As a researcher, he has worked on many projects focusing on horticultural and floriculture crop systems by investigating the agronomic, physiological, and biochemical aspects. His studies are focused on production quality control, examining environmental sustainability in open fields as well as in vitro and in greenhouse cultivation. Caser has collaborated with Meiji University in Tokyo and at the Botanical Garden in Niigata (Japan); at the Kunming Institute of Botany, Chinese Academy of Sciences (Kunming, China), where he researched ornamental characteristics in azaleas and rhododendrons; at the Institute for Agricultural and Fisheries Research, Plant Sciences Unit (ILVO) in Ghent (Belgium), where he worked on flow cytometry, microscopy, and participated in a qPCR course as part of an integrated stage in the EU Marie-Curie action Project; and at the Eduardo Mondlane University (Maputo, Mozambico), where he worked on the propagation of endemic species.

Recently, he has been involved in four projects, one funded by the European Commission; another one by the Italian Ministry of Culture aiming at the "Regeneration of small cultural, cultural, religious, and rural sites"; and a "Program to enhance the identity of places: historical parks and gardens". He authored about 100 scientific publications, published several books in the field of floriculture, and has participated in over 30 conferences.

He is a member of the "Società Orticola Italiana" and of International Society for Horticultural Science (ISHS) and serves as a peer reviewer of international academic journals.

Preface

The 21st century demonstrates that global cities face increasing pressures in the socio-ecological sphere. Despite digital dematerialization, urgent issues like climate change highlight the importance of the physical world and cities. Thus, disciplines such as urban planning, green urban design, architecture, and agricultural sciences are collaborating to propose future solutions for cities that go beyond mitigation and adaptation.

This reprint explores how these combined disciplines can produce resilient solutions to future-proof cities by 2050. The sustainable use of ecosystem services is crucial for urban futures. How should architecture and urbanism adapt to changing conditions? Which settlement models should address emergencies from a multi-level perspective? How can medicine influence planning choices? What contributions can agricultural, horticultural, forestry, and agronomic sciences offer beyond planning tools like green and blue infrastructures?

This reprint addresses theoretical proposals, practical case studies, and interdisciplinary research to build a registry of common actions and strategies that can discuss and update the UN SDG 11 (2015). It focuses on topics related to planning, such as integrated policies, regional development policies, and programs to future-proof cities. It also addresses architecture, focusing on city modifications related to climate, urban, and peri-urban protection and enhancement. Additionally, it explores agriculture and horticulture, urban horticulture, sustainable cultivation, urban green design, and ecosystem services, all aimed at contributing to social, environmental, and economic sustainability.

This Special Issue identifies recurring topics. Several papers discuss the role and benefits of urban green spaces, focusing on environmental sustainability and public health. The included studies explore enhancing city resilience to climate change through green infrastructure and sustainable planning. Another theme is integrating sustainability into urban development, including promoting green buildings and sustainable transportation. The included papers also address biodiversity preservation within urban environments, highlighting urban biodiversity conservation strategies. Additionally, there is a focus on the social dimensions of urban green development, including the role of green spaces in improving community well-being, social cohesion, and quality of life. Some papers examine the role of policy and governance in promoting urban green development, including implementing green policies and urban governance challenges. Innovations in technology for sustainable urban development, such as smart cities and digital tools for urban planning, are also recurring topics.

These subjects highlight a comprehensive approach to urban sustainability and resilience, emphasizing the multifaceted benefits and challenges of integrating green development into urban planning and architecture.

Marco Devecchi, Fabrizio Aimar, and Matteo Caser
Editors

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Article

Developing a Conceptual Framework for Characterizing and Measuring Social Resilience in Blue-Green Infrastructure (BGI)

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Abstract: Many cities are increasingly adopting blue-green infrastructure (BGI) to bolster their resilience against environmental challenges. Beyond its well-acknowledged environmental benefits, the role of BGI in enhancing social resilience is becoming an equally important area of focus. However, the integration of BGI in fostering social resilience presents complexities, stemming from the evolving and occasionally ambiguous definition of social resilience. Considering the broad application of BGI across various disciplines makes the evaluation of social resilience within a BGI framework complex. Consequently, a structured approach to develop a clear framework tailored to understanding and measuring social resilience in a BGI setting is needed. This study consolidates various existing frameworks of social resilience, especially utilizing the detailed 5S framework proposed by Saja et al. It integrates findings from an extensive review of literature on social resilience to develop a novel conceptual framework—the BGI Social Resilience Framework. This new framework specifically aims to capture the distinct social aspects and advantages associated with BGI. The BGI Social Resilience Framework is organized into a three-tier model, focusing on four critical aspects of social resilience—social values, social capital, social structure, and social equity—and explores how these aspects are interconnected. Characteristics and indicators are customized to accommodate the context of BGI in a way that integrates the physical and human dimensions within a comprehensive approach to measurement that uses a combination of qualitative and quantitative methods. Specifically, this research formulates a theoretical framework for BGI with the aim of investigating BGI strategies and viewpoints that bolster social resilience. The BGI Social Resilience Framework takes into account the varied demographics and the physical characteristics of urban areas to explore ways to create BGI spaces that are more inclusive and that contribute to the enhancement of social resilience.

Keywords: blue-green infrastructure; social resilience; urban sustainability

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1. Introduction

According to United Nations projections, two-thirds of the global population will reside in urban areas by 2050 [1]. This rapid urban growth and suboptimal development practices intensify the issues faced by communities, especially those related to climate change, heightened disaster risk, and social fragmentation [2–4]. In response to these pressures, blue-green infrastructure (BGI) is increasingly recognized for its multifaceted benefits, encompassing environmental, social, cultural, and public health aspects [5–9]. Although BGI is typically introduced due to its ability to manage stormater and mitigate climate change impacts [5], BGI plays a pivotal role in nurturing social connections within communities, which is essential to building social resilience [7]. The establishment of these social connections stands out as a fundamental characteristic of a resilient community, which is a key component of building social resilience [10].

In response to the role of BGI in fostering social resilience, this research introduces a conceptual framework designed to foster social resilience within urban settings through the strategic integration of BGI. This framework is developed from an extensive examination of the current literature on social resilience theories and frameworks and the unique contribution of BGI spaces. The framework seeks to fill an identified gap in current research and applications by providing specialized insights into planning and developing BGI to enhance social resilience equitably across diverse community demographics.

Foundational to this debate is the definition of BGI as an interconnected planned network of natural and semi-natural 'blue green' landscape components designed to deliver a wide range of ecosystem services at various scales [11]. From a social perspective, these spaces serve as communal hubs where people gather, interact, and engage in shared activities that help to improve a community's resilience profile [9]. These regular interactions in BGI spaces foster attributes of social capital such as trust, solidarity, and a sense of belonging [12,13] within the community. Social capital is recognized as a vital component of social resilience, enhancing the collective strength and adaptive capacity of communities to effectively tackle contemporary challenges [14].

Furthermore, these spaces are catalysts for social learning, information exchange, and problem-solving skills, enhancing a community's adaptive capacity and ability to respond to contemporary challenges, both foundational for resilience [15]. Activities within these spaces are pivotal in strengthening and broadening social networks and fostering collaborative efforts. They also create platforms where communities can share information and implement collective solutions to common challenges [16–18]. Importantly, the social connections forged in these settings contribute significantly to the mental and emotional wellbeing of individuals, thereby enhancing overall community resilience [19].

These interactions demonstrate a dynamic exchange where BGI spaces are integral for community development and are supported by the communities they serve. The significant role of BGI in enhancing community socialization and capacity-building underscores its crucial contribution to building communities that are resilient, inclusive, and adaptive [14,20,21]. This understanding has led scholars, practitioners, and policymakers to regard BGI as an essential element of urban resilience strategies [5,7,8,22,23]. The broad acknowledgment of BGI benefits across various sectors highlights its pivotal role in the holistic development of sustainable and healthy urban environments.

Despite the recognized value of BGI, a clear and concise framework for assessing social resilience in these spaces is needed [24]. Specifically, there needs to be a clearer understanding of the attributes and practices that foster social resilience, while meeting the diverse needs of communities [25,26]. However, this is challenging due to social resilience's inherent complexity and ambiguity and variations in frameworks interpretations and applications across diverse contexts [24,27].

Social resilience is studied and applied across many disciplines, and like many other interdisciplinary concepts, definitions of social resilience vary across the literature. Earlier, social resilience was defined as the ability or capacity of a social entity, such as an individual, community, or organization, to absorb, cope, and adjust to disturbances and threats because of social, political, and environmental changes [28,29]. This definition focuses on the capacities of social entities to protect themselves from all kinds of hazards and threats.

As social resilience gained more prominence in the field of urban planning, it was referred to not only as a response to threats and disturbances or crisis planning, but also as a means of strengthening social ties, improving wellbeing, and addressing inequities that may exist for vulnerable or marginalized groups [30]. Studies highlight the importance of fostering trust and cooperation, understanding cultural practices and social norms, and the capabilities to assimilate knowledge and learning within these frameworks as essential for building and maintaining resilience [18,31,32]. Today, social resilience is recognized as a critical component of sustainable urban development, particularly in fostering thriving and healthy communities [33,34].

Early case study research on social resilience focused on various threats and stressors across temporal and spatial scales. These are broadly grouped in three categories: (1) disaster management [35–37], (2) resource management and ecological urban resilience [28,38,39], and (3) social change and development referencing policy and institutional change [40,41]. Across these categories are themes of learning, adaptation, and the recognition of political dynamics and processes [42].

A diverse array of frameworks for assessing social resilience has emerged, each varying in its approach, focus, and breadth of characteristics and indicators [24,27]. Many of these frameworks are rooted in disaster resilience literature, with a predominant emphasis on disaster risk, response, and management [20,24,27]. Many of these frameworks focus on the role of social connections and relationships within the context of disaster preparedness, emphasizing their importance as support networks during emergencies or as channels for information and resource sharing post-crisis [27,43,44]. While this context is essential, there is also a growing recognition of the broader potential of social dynamics in enhancing community health and wellbeing [45–47].

This expanded view encourages a comprehensive approach that includes strengthening community bonds, promoting wellbeing, and ensuring equity as key components of social resilience. Within this framing, BGI presents an ideal context for cultivating these relationships [7,20,48,49] and can be a tool for creating equity [50,51]. This expands the focus beyond mere disaster resilience to encompass the development of healthy, interconnected communities.

Acknowledging the insights from the existing literature on the lack of a comprehensive framework for characterizing and measuring social resilience within disaster contexts, the challenge becomes even more pronounced when integrating BGI within a broader resilience framework. This gap limits the understanding of the potential of BGI in strengthening social resilience, emphasizing a need for a comprehensive approach that extends beyond conventional scopes and delves into the nuanced interplay between BGI and social resilience in urban settings.

This manuscript presents a new conceptual framework for characterizing and measuring social resilience within the context of BGI. It is driven by the primary research question: How can a social resilience framework be developed and operationalized for the BGI context to foster social resilience amidst urban growth and its challenges? This overarching question is explored through several sub-questions: What are the key elements of established social resilience frameworks, and how might they inform the development of a framework for BGI? How can a selection of characteristics and indicators from existing frameworks be adapted for social resilience in a BGI context? What methods can be integrated to operationalize a methodologically robust BGI social resilience framework? What specific measurement and implementation methods can be integrated to ensure the operational success and methodologically robust social resilience framework for BGI?

The new BGI Social Resilience Framework synthesizes urban spatial features with BGI practices. It is specifically designed to address disaster resilience and broaden the scope to include key aspects of community health and wellbeing. This approach enhances social connections and promotes equity, reflecting a comprehensive strategy for understanding and improving urban resilience in diverse community settings.

This manuscript unfolds across three interconnected stages, beginning with an examination of challenges and complexities in defining and applying social resilience, as well as existing frameworks (Phase 1). This is followed by adapting social resilience characteristics and indicators specific to the BGI context (Phase 2). The final stage (Phase 3) involves developing a tailored social resilience framework for BGI, grounded in a comprehensive literature review that helps to identify and integrate relevant social resilience features into BGI. The document concludes by charting a course for future case study research.

2. Applying Social Resilience Framework Concepts to BGI

The methodology for developing a conceptual framework for BGI entails a three-phase approach: (i) conducting a systematic review of the academic literature on social resilience frameworks, (ii) adapting the framework elements specifically for BGI, and (iii) developing the structure and organization of a new conceptual framework. This literature review critically evaluates prevailing conceptual methods, metrics, and indicators to identify notable frameworks to inform the BGI Social Resilience Framework development. The reviewed frameworks are then critically examined, extracting relevant themes and concepts, and identifying gaps to address in the proposed BGI framework. Key themes, characteristics, and indicators are analyzed for their applicability in the BGI context. Lastly, these learnings are synthesized to present a comprehensive conceptualization and methodology for a new conceptual framework for the BGI context, called the BGI Social Resilience Framework.

2.1. Phase 1 Literature Review: Identification of the Challenges and Complexities in Defining and Operationalizing Social Resilience, and Relevant Social Resilient Frameworks

A systematic literature review was conducted to identify and examine social resilience frameworks to uncover inherent challenges and complexities and assess their pragmatic applicably across diverse contextual landscapes. The selection of literature encompassed a broad range of approaches, integrating insights from disaster management, social change, and urban development to facilitate a comprehensive analysis that extends beyond traditional disaster scenarios. This process is instrumental in identifying notable gaps and refining key elements necessary to effectively address the complex dynamics of social resilience in the development of a new framework for BGI.

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [52] method was used to conduct a systematic and thorough review of resilience frameworks. The PRISMA method is based on four steps: (1) identification, (2) screening, (3) eligibility, and (4) inclusion. Each step is outlined below, and correspondingly illustrated in the flowchart shown in Figure 1.

- Identification: An extensive search was conducted through the Scopus and Google Scholar databases using the terms "Social" OR "Community" AND "Resilience", resulting in a large pool of literature, 25,000 Google Scholar and 62,209 Scopus, providing a vast base for initial consideration.
- Screening: The literature review was refined by limiting to the subject areas most closely aligned to BGI and urban planning, including social science, engineering, environmental science, and multidisciplinary studies, the English language, and journals relating to disaster, risk, and sustainable resilient cities and communities; 3356 articles were identified.
- Eligibility: The titles of the 3356 articles were screened to narrow the search for the most relevant articles on social resilience. The title and abstracts of articles that do not relate to social or community resilience, disaster, or sustainability were excluded. In total, 175 articles were identified for further review.
- Inclusion: The abstracts of the 175 articles were reviewed, and 23 articles were selected based on content with abstracts referencing health, wellbeing, and/or sustainability are prioritized. A detailed review of the full texts specifically identified two notable frameworks that were particularly important to the development of the BGI Social Resilience Framework. The first, proposed by Saja et al. [24], is distinguished by its comprehensive synthesis of existing frameworks, clear organizational structure for operationalization, and the breadth of themes that can be applied to the BGI context, making it a robust template for the new framework. The second framework by Kwok et al. [20] is distinguished by its use of practitioner perspectives, utilizing practitioner perspectives, which incorporate subjective insights essential for capturing the nuanced, context-specific experiences crucial to developing practical and effective resilience strategies. Together, these two enrich the new framework with both wide-ranging theoretical foundations and practical grounded insights through the less-used subjective lens. They are summarized with critical learnings for application in the BGI context.

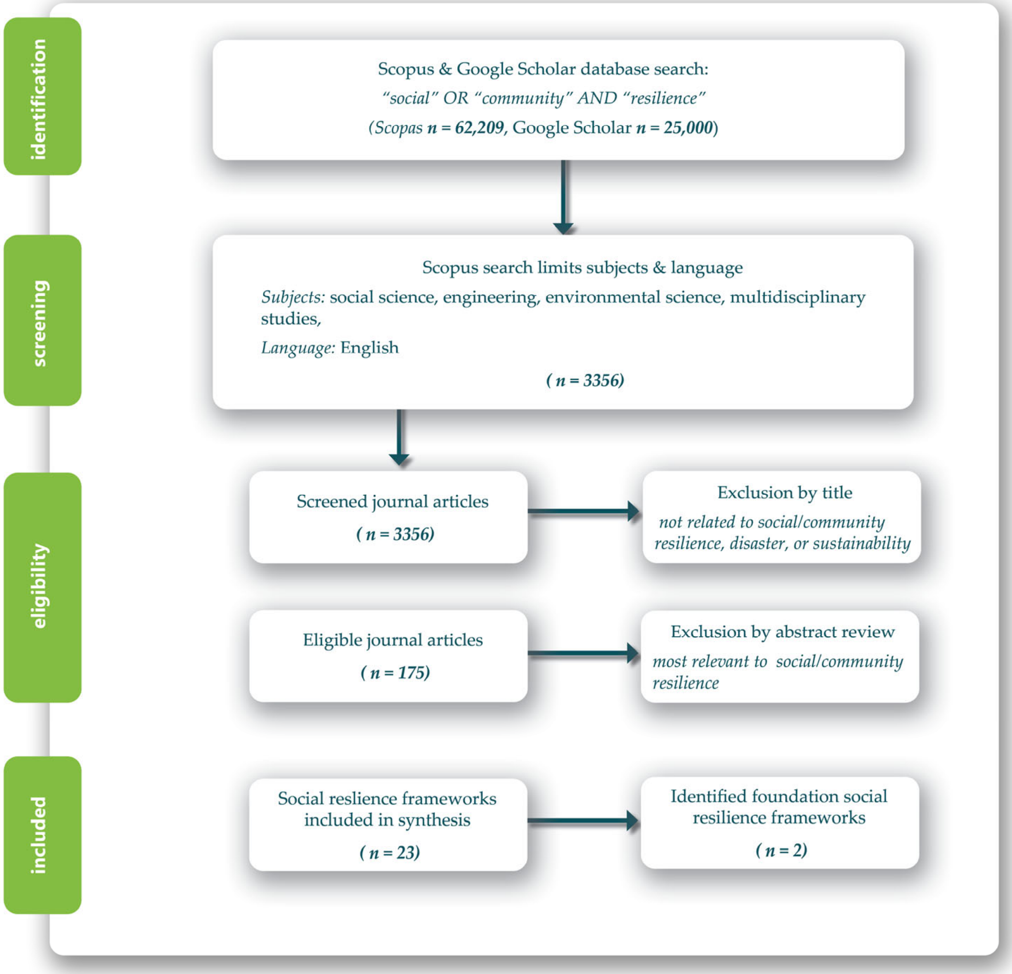

Figure 1. Article selection process flowchart.

2.2. Phase 2: Adapting Social Resilience Characteristics and Indicators to the BGI Context

The second phase primarily focused on adapting the social resilience characteristics and indicators to the BGI context, drawing upon the foundational work of Saja et al. [24] and Kwok et al. [20], alongside other frameworks identified in the comprehensive review of related literature. Additionally, the process was enriched by incorporating insights from current BGI practices and literature. This phase was pivotal in refining and customizing the framework to ensure it was theoretically sound and practically relevant to BGI environments.

As a part of the adaptation process, characteristics and indicators are embedded in the key dimensions of social resilience such as social values, social capital, social structure, and social equity, as detailed in the 5S framework by Saja et al. [24]. These dimensions are essential for developing comprehensive resilience strategies, making the 5S framework an ideal foundational template for the BGI Social Resilience Framework. The selection of characteristics and indicators was informed by those shared between the works of Saja et al. [24] and Kwok et al. [20], as well as additional insights from the literature review. This approach ensured a balance of common and uniquely relevant elements. The criteria for choosing specific characteristics were further refined based on their relevance to urban BGI settings, their scalability at the community level, and their potential to enhance the understanding of a broader conceptualization of social resilience, thereby expanding its application beyond traditional disaster resilience contexts.

The selection and adaptation effort aims to bridge theoretical research with practical application, emphasizing characteristics and indicators that are particularly relevant to urban BGI contexts and social systems with a special focus on fostering community-scale social dimensions and prioritizing aspects of wellbeing and equity.

2.3. Phase 3: Developing the BGI Social Resilience Framework

This phase synthesized insights from Phases 1 and 2 to develop a new BGI Social Resilience Framework. The newly developed framework utilizes the organizational structure outlined in the 5S framework by Saja et al. [24] and enhances it with the community-centric perspectives from the practitioner framework by Kwok et al. [20]. The integration of these foundational frameworks facilitates a comprehensive approach, incorporating both the broad thematic synthesis of social resilience indicators from the 5S framework and the nuanced, subjective insights into community dynamics and perceptions from the practitioner framework. This blend ensures that the BGI Social Resilience Framework not only adheres to a structured methodological approach, but also remains deeply rooted in the realities and values of community experiences.

To address the need for a methodologically robust tool that can guide the operationalization of BGI for social resilience, this phase introduces an innovative fourth tier to the framework. This tier provides specific guidance on measurement tools and techniques, reflecting the integrated insights from both foundational frameworks. It aims to operationalize the framework within the BGI context (Phase 2) by identifying and outlining methods that can measure the interplay between BGI attributes and social resilience dimensions effectively. This addition marks a significant advancement, offering a methodologically sound and contextually relevant tool for planning and developing BGI with a focus on enhancing social resilience across diverse urban communities.

Furthermore, this phase ensures that the BGI Social Resilience Framework is tailored to address broader resilience concepts, including sustainability and wellbeing, reflecting the unique advantages BGI offers in urban environments. By focusing on both the structural and cognitive aspects of social systems, ranging from demographics and accessibility to community perceptions and engagement, the framework bridges the gap between physical BGI features and the community's social dynamics. This dual focus underscores the framework's holistic approach, emphasizing how the physical infrastructure of BGI and social cohesion work together to foster resilient communities.

This methodological approach not only enhances the BGI Social Resilience Framework's operationalization, but sets a new precedent for comprehensive, evidence-based planning tools that can be used to adaptively respond to the complexities of urban social resilience.

3. Synthesizing Social Resilience Frameworks for BGI Context

3.1. Challenges and Complexities in Defining and Operationalizing Social Resilience across Disciplines

Drawing from the extensive literature review (Phase 1), the concept of resilience has evolved significantly, cutting across multiple research fields and introducing complexity and ambiguity. Each discipline contributes its unique definition and conceptualization, creating notable inconsistencies in data collection and measurement methodologies [53]. This variability presents significant challenges, operationalizing resilience into practical applications [54].

In the realm of social resilience, these challenges are exacerbated by the concept's abstract and multi-oriented nature that involve inter-related properties within complex and dynamic social systems [24]. These systems are spatially and temporally bound, meaning that the levels of social resilience change throughout a disturbance cycle [55] and are highly influenced by place and community [20,56]. This makes it difficult to isolate factors and apply uniform resilience strategies across different contexts and scales.

A further complication in resilience applications are a lack of clarity in the literature regarding which characteristics and indicators needs be measured and understood in terms of how these intertwine with sustainability in practice [57,58]. The urban planning sector, for example, employs several frameworks to assess social resilience within the disaster and natural hazards context, each with its diverse approach and multitude of subdimensions, characteristics, and indicators [59–61].

While there is some consistency in the sub-dimensions within social resilience frameworks, the range of characteristics and indicators is quite broad [62]. Saja et al. [24] analyzed 31 existing frameworks and identified 80 unique characteristics and indicators related to social resilience, yet no single predominant concept for framework development emerged. An extensive review by Cutter et al. [27] of 27 different resilience tools, indices, and scorecards further confirms the lack of a dominant approach, with no clear set of characteristics consistently emerging across the various frameworks.

3.1.1. Conceptualization and Context

The lack of clarity and consistency on how social resilience is defined has resulted in confusion about how key concepts are understood, interpreted, and applied. The basic framework for adapting to a particular resilience concept has no uniform approach [61], leading to diverse conceptualizations. These can range from focusing on various types of capital to emphasizing singular dimensional attributes or considering different stages within a resilience cycle to establishing unique, stand-alone frameworks encompassing numerous key characteristics of social resilience [27,61]. Such conceptual variations significantly impact the metrics and methods of measurement, complicating the ability to compare findings across different research efforts [27,62].

Saja et al. [61] outlines the following social capital conceptualizations. These are graphically illustrated in Figure 2.

- Capital-based: emphasis on social capital with different types of social assets that can be attributed to key social resilience characteristics.
- Coping, adaptive, transformative (CAT) capacities: captures the dynamic attributes of social systems on multiple scales.
- Social and interconnected community resilience: social resilience within a holistic, multidimensional characteristic of community resilience.
- Structural and cognitive dimensions: discrete features of a social entity, people, and communities (structural) and attitudes, values, beliefs, and perceptions (cognitive).

Further complicating the landscape are the distinguishing properties such as a scalar unit of analysis, geographic context, and hazard type, each introducing distinct attributes and measurement challenges [27,61]. Considering the scale and the household level, the focus tends to be on financial stability and access to essential resources and access to social safety nets [63] while community resilience emphasizes cohesion and diverse value systems [14,59,64]. City-scale resilience prioritizes infrastructure and the built environment's disaster readiness [5,33,65,66], whereas global resilience considerations span broader environmental impacts, such large food systems, biodiversity, and disease [67].

In comparing urban and rural contexts, the underlying factors of resilience diverge. Urban resilience tends to rely on economic capital, while in rural areas, the key to disaster resilience lies within community capital [27,61]. Lastly, the specific nature of hazards, from gradual threats like rising sea levels to immediate crises like earthquakes, necessitates tailored resilience strategies. This variability across different scales and contexts highlights the complexity of developing a unified approach to measuring social resilience, emphasizing the need for flexibility and specificity in resilience planning and measurement.

Figure 2. Four types of social resilience conceptualizations adapted from the work presented in [61].

3.1.2. Methodology and Indicators

The ambiguity and process orientation dimension inherent in the concept of social resilience presents challenges in its quantification and measurement [24,27]. This lack of clarity has resulted in variability in methodology types and uncertainties about what should be measured [24,27]. Furthermore, current frameworks are critiqued for not adequately capturing the dynamic, transformative, and recovery aspects of resilience [24,68] and for overlooking the normative implications in defining communities and their attributes as indicators [68].

According to systemic reviews of social resilience frameworks, the most common measurement strategy uses characteristics with corresponding indicators [24,27,68]. The indicator method is also the preferred approach of agencies and practitioners [24]. Other methods include scorecards, an aggregate of scores indicating how often the items are present and scorecards that guide through sample procedures, survey instruments, or data for use [27].

When examining the character-indicator method, these challenges are further exacerbated by the limited guidance regarding the appropriate characteristics and indicators to use within a specific purpose or context [27]. It is essential to distinguish between characteristics and indicators. Characteristics help to characterize an ideal state of resilience in general terms [69], while an indicator describes measurable information used to identify a social entity's state or function [61].An indicator, or set of indicators, measures a resilience characteristic [61]. Resilience indicators are instrumental in defining the fundamental components of the system or entity under study and help to facilitate increased community awareness [70]. Additionally, they are crucial in guiding communities in evaluating and prioritizing their needs and objectives [27].

To measure social resilience effectively, three types of indicators are commonly utilized: outcome, process indicators, and normative [24,27,61]. Each type of indicator serves a distinct purpose, with their differentiation elaborated upon below.

- Outcome indicators capture the static results or how well processes, interventions, or programs accomplish a proposed result. They represent the final or observable outcomes to achieve or measure. Outcomes include a faster recovery time, improved wellbeing, community cohesion, disaster preparedness, and risk reduction [24,27,61].
- Process: Process indicators typically capture the dynamic and ongoing aspects of a phenomenon. They focus on the activities, behaviors, or steps involved in a process, intervention, or program. They are valuable for assessing whether participants actively engage with and respond to an intervention. Examples may include the level of engagement, the frequency of communication, and a feeling of belonging to a community [24,27,61].
- Normative: shared beliefs, principles, and standards that guide the behavior of interactions of individuals in a community [61].

Many social resilience frameworks focus on static outcome indicators rather than process-related ones because they are more accessible and relatively easy to measure [24,61]. However, understanding social resilience requires a broader lens that includes process-related indicators, such as community competence, information dissemination, and community participation, which are vital but more complex to quantify [53]. Additionally, normative indicators play a pivotal role in capturing a community's unique character and context, reflecting the local values and priorities that define what is essential to its members [61].

To navigate these complexities effectively, refining resilience frameworks to include a balance of outcome, process, and normative indicators, each offering valuable insights into the different facets of social resilience, is essential. Such a comprehensive approach will provide a more accurate and actionable understanding of resilience, enabling communities to develop targeted strategies for enhancing their collective strength and adaptability.

3.1.3. Summary

Table 1 comprehensively summarizes the challenges and complexities discussed in previous sections. The spectrum of dimensions is categorized, described, and linked to specific frameworks that utilize each concept and method. This table synthesizes the field's heterogeneity, demonstrating the range of existing analytical methods while tracing their usage in an established resilience framework.

Table 1. Conceptual and methodological spectrum of the social resilience frameworks.

Dimension		Description	Framework References
Conceptualization	Structural and cognitive	Encompasses (structural) discrete features and characteristics of a social entity and (cognitive) attitudes, values, and beliefs.	[24]
	Coping, adaptive, transformation	Capacities of communities to cope, adapt, and transform to dynamic challenges; embracing change, and fostering long-term sustainability and growth.	[71,72]
	Social and interconnected	Web of relationships and networks within a community, underscoring the role of social ties, collective action, and the integration of diverse community resources in building resilience.	[24,35,73]
	Capital-based	Resilience in terms of capital and strategic deployment of resources as essential.	[74–76]
Context	Hazard specific	e.g., earthquake, flood, drought, sea level rise.	[77,78]
	Geographical context	urban, coastal, rural, city, mountains, islands.	[43,78–80]
	Hierarchical scale	Individual, community, governmental.	[61,81]
Assessment type	Indicator	Observable measurable characteristics/change representing resilience characteristics.	[24,75–77,82]
	Scorecard	Aggregate of score based on how often the items are present, often providing an evaluation of progress to goal.	[83,84]
	Toolkit	Guidance through a set of tools, methodologies, and guidelines that encompass a range of resources, such as best practices and case studies.	[85–87]
Indicator type	Outcome	How well interventions accomplish a result.	[27,61,77,82]
	Process	Level of engagement in a phenomenon.	[27,61,77,82]
	Normative	Shared beliefs and values guiding behavior	[20,68]

3.2. Key Resilience Frameworks

This literature review notably identifies two frameworks, which emerged as foundational for the development of a BGI-specific framework. These frameworks are: 'An inclusive and adaptive framework for measuring social resilience to disasters' [24] and 'What is 'social resilience'?', including the perspectives of disaster researchers, emergency management practitioners, and policymakers in Aotearoa New Zealand disasters [20]. For ease of reference, these will be termed the 5S framework and the practitioner framework throughout this discussion.

The 5S framework serves as a comprehensive synthesis of existing social resilience methodologies, presenting a robust structural approach with a broad thematic scope [24]. This framework not only integrates a spectrum of prevalent themes, but also organizes them in a manner conducive to operationalization across diverse contexts, including those pertaining to BGI. It is recognized as a flexible template designed to guide future research and practical applications and is utilized for this purpose.

The practitioner framework is distinguished by its bottom-up, community-place-based approach, capturing direct insights from practitioners. Utilizing interviews to derive subjective insights, it delves into the nuanced, context-specific experiences that are not often captured in conventional frameworks. This methodological approach infuses the framework with personal insights, offering a distinct perspective on social resilience. It thus enhances the 5S framework by incorporating practical, actionable strategies into the established theoretical foundations [20].

Collectively, these frameworks establish a robust theoretical foundation for the newly proposed BGI Social Resilience Framework, enriched with empirical and contextually specific insights. This integrative approach not only ensures comprehensiveness but also grounds the framework in practical realities, thereby enhancing its applicability to effectively address the distinct challenges and requirements of BGI contexts.

3.2.1. Inclusive and Adaptive 5S Framework

The development of the 5S framework is based on a critical review of existing social resilience frameworks which identified inconsistencies in how social resilience is understood. Saja et al. [24] undertook a comprehensive review of 31 existing frameworks, with the goal of standardizing the benchmarking and synthesizing key social resilience characteristics and indicators to create a versatile model applicable across diverse contexts. To structure the 5S framework effectively, a matrix was constructed from the identified characteristics and indicators of these frameworks, re-clustering the characteristics to pinpoint commonalities and then assigning the most frequently used indicators for each characteristic. Lastly, the characteristics were thematically clustered to generate the five sub-dimensions that form the frameworks' structure. Each layer in the framework builds upon the previous, creating a cohesive and interconnected structure. This sequential layering is depicted in the process and the resulting three-layer framework is illustrated in Figure 3.

The 5S framework provides key learnings for developing a BGI-specific framework by addressing the challenges of measuring social resilience through a structured and evidence-based approach [24]. Its strengths lie in the methodological rigor that identifies common themes and concepts pivotal for social resilience, integrating a balanced mix of outcome and process indicators. The 5S framework is structured around widely recognized subdimensions of social resilience, featuring a clear, tiered design that effectively captures the transformative and recovery aspects of resilience. This includes facets such as volunteerism, community engagement strategies, and information and communication channels, which are essential for inclusive engagement and capacity building within communities [18,88,89].

However, the application of the 5S framework reveals the limitations that need addressing to enhance its practicality in a BGI context. Its complexity and the broad spectrum of indicators necessitate a focused refinement to better suit the non-disaster specific aspects of social resilience, such as strengthening social connections and addressing wellbeing and equity concerns. The framework's scale variability also indicates the need for a more singular focus that resonates with community-level interactions that take place in BGI. Furthermore, the absence of detailed guidance on measurement tools underscores the importance of contextualizing the indicators that can capture place. While it is well-grounded in robust theory, there is no clear mechanism to understanding the subjective dimensions of the community that play an important role in resilience [21]. By considering these limitations and incorporating direct community input, the BGI Social Resilience Framework can avoid potential disconnects between theoretical constructs and the lived experiences of communities, ensuring a more grounded and responsive approach to building social resilience through BGI.

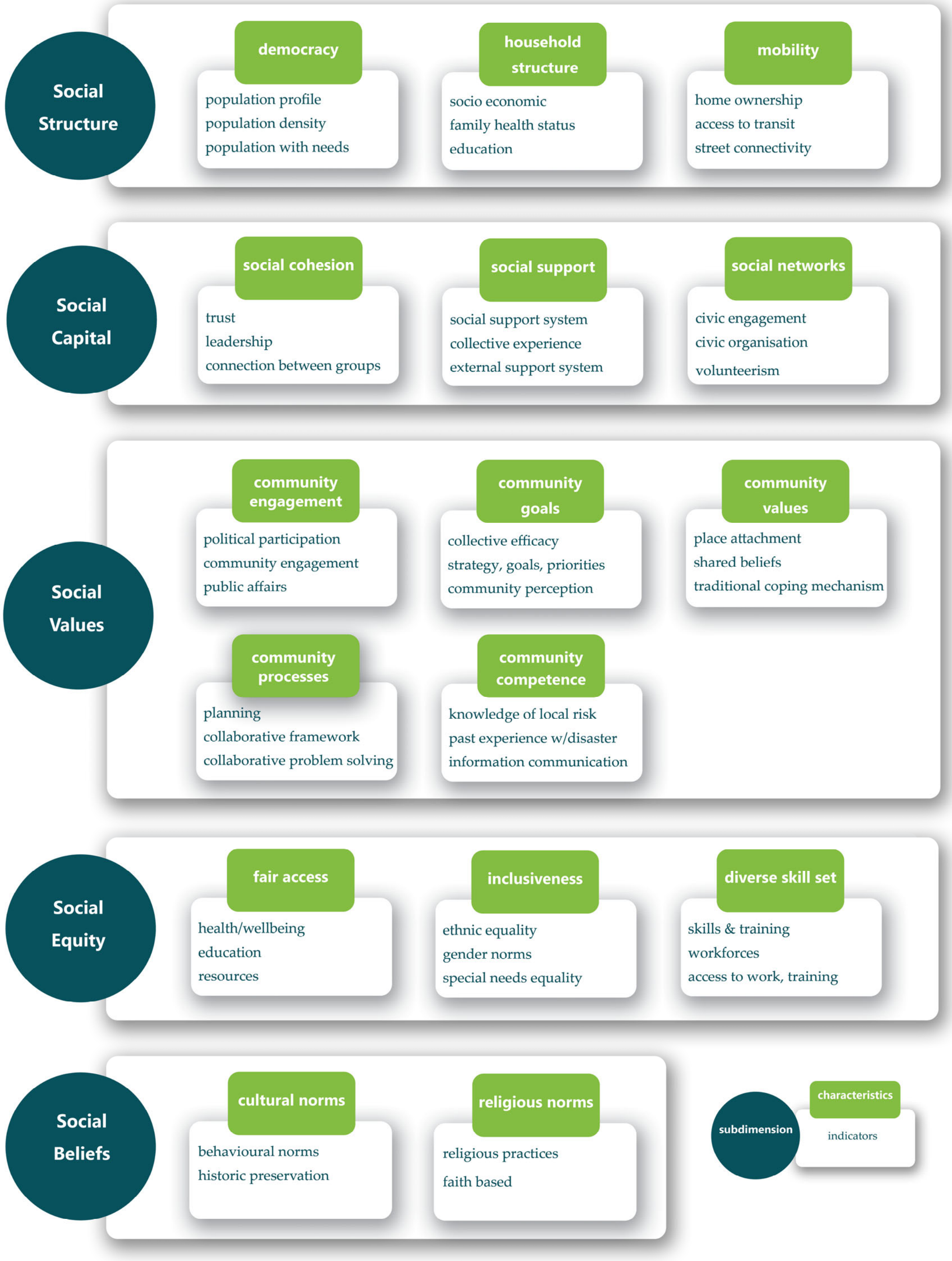

Figure 3. An inclusive and adaptive '5S' social resilience framework adapted from the work presented in [24].

3.2.2. Practitioner Perspectives from Aotearoa New Zealand

Research by Kwok et al. [20] seeks to capture the nuances of social resilience from the community perspective. Conducted through workshops in Aotearoa New Zealand, it utilizes group interviews to explore participants' views on social resilience, identify key contributing elements, and pinpoint initiatives for enhancing community resilience. The study led to the identification of 66 social resilience attributes, with particular emphasis on the significance of place, relationships, learning, and governance. These attributes, reflecting both cognitive and structural dimensions, span across human capital, economic resilience, the built environment, and governance, and are considered essential for strengthening community resilience. The outcomes of this research have been synthesized into a set of core attributes and actionable strategies, offering a robust framework for agencies to support resilience-building efforts within communities. The core attributes of social resilience of communities and accompanying resilience-enhancing actions are outlined in the framework in Figure 4.

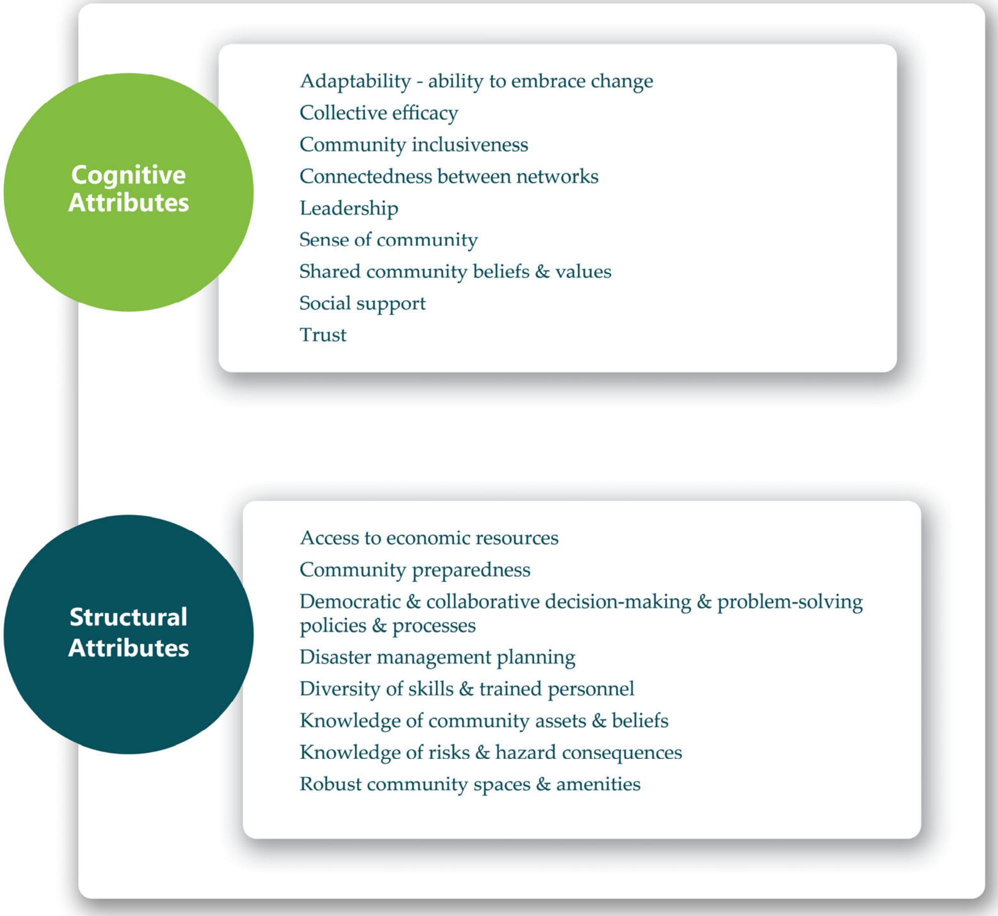

Figure 4. Core attributes of the social resilience of communities adapted from the work presented in [20].

The practitioner framework, through its blend of interview insights and literature review, offers a compelling approach for integrating human-centric considerations into the understanding of social resilience at a community level. It stands out for its structural and cognitive categorization of attributes, which clarifies the distinction between the tangible aspects of resilience and the underlying cultural or behavioral dynamics. This framework is particularly valuable for its place-based focus, capturing the intricacies of local dynamics through a bottom-up approach that reveals the normative and perceptual components essential for resilience. These insights are crucial for BGI framework development, emphasizing the role of natural environments and community spaces as pivotal in fostering social ties and resilience.

However, while the practitioner framework excels in theoretical organization, it encounters practical challenges, notably the absence of direct community engagement in its development process. This gap suggests a potential disconnect between the framework's structure and the lived realities of the communities it seeks to serve. Despite these limitations, the framework's emphasis on actionable items and its recognition of greenspaces and community gatherings as essential for building social resilience provide a strong foundation for BGI considerations. By incorporating these elements, the BGI Social Resilience Framework can more effectively capture both the physical infrastructure and the social cohesion necessary for resilient communities, aiming to strike a balance between comprehensive planning and the adaptability required for diverse urban settings.

3.3. Selection of Characteristics and Indicators for the BGI Context

Drawing from the organizational structure of the 5S framework [24], the BGI Social Resilience Framework adopts a similar three-tiered approach that includes sub-dimensions, characteristics, and indicators. The BGI Social Resilience Framework retains the four critical dimensions of social resilience: social values and beliefs, social capital, social structure, and social characteristics. Additionally, it tailors the characteristics and indicators to align with the dynamics and demands of the urban BGI context.

Characteristics guide the conceptual mapping by describing the inherent properties of social resilience. In contrast, indicators are specific, quantifiable measures that can be used to evaluate these characteristics [24]. The selection of characteristics and corresponding indicators is informed by the inter-relationships between these dimensions and the broader BGI literature. Characteristics shared between the frameworks in the literature that are particularly pertinent to community-scale social dimensions of BGI have further shaped this guidance. A detailed examination of the characteristics and corresponding indicators are presented in the subsequent sections.

3.3.1. Social Values and Beliefs

Local culture, social beliefs, and shared values play a significant role in determining social resilience [20]. These elements are not just abstract concepts but have a tangible impact on how communities forge strong social networks, adapt to challenges, and enhance their resilience [18,90,91]. Furthermore, these shared values and beliefs are instrumental in guiding collective actions and influencing the community's preferences towards various resilience strategies [24].

Social values in this context consist of two types of values: (1) held values: ideas or principles that people hold as important to them and (2) assigned values: values that individuals attach to physical places [92,93]. Generally, held values are broader and refer to ethical, moral, or ideological values, while assigned values are specific to a place and may include aesthetic, therapeutic, and cultural values [94]. Unlike held values, assigned values are not absolute because they are influenced by context and the perceptions and preferences of an individual [93]. These values are oriented by beliefs or ideologies and influence an individual's attitude and behavior, with context further influencing perceptions [95]. Together, these subjective dimensions (values and beliefs) provide a lens through which people perceive the world and enrich our understanding of human processes, behavior, and preferences [96,97].

In the domain of BGI, the subjective dimensions such as users' sense of safety, satisfaction with spaces, perceptions of sociability and quality, as well as preferences towards activity, aesthetics, and size serve as a cornerstone for its efficacy [21,98]. These dimensions affect how and whether people engage with these spaces [99,100] and the degree for which this engagement translates to community interactions [101,102]. They are a stronger predictor for the frequency of visits [103], the development of social networks [21], and whether users engage in activities [103], compared to objective dimensions.

Given that these dimensions are influenced by personal experiences and cultural ideologies, they exhibit varying qualities across demographic groups [104–106]. Research on greenspace engagement provides valuable insights into the diverse preferences and levels of engagement among different demographic groups, emphasizing the crucial role of demographics in understanding individuals' interactions with spaces [107]. Examples of preference variability include women and passive use, older adults and nature-based activities, and younger people and social uses [25,108]. Women [109], youth of color [110], and people with disabilities have more significant concerns around safety [111] and these concerns can often discourage their use of spaces.

This intersection of perception and practice that captures a wide array of user experiences, attitudes, and actions with BGI is important to understand. It not only dictates the level of interaction between community members and BGI, but also reflects the subjective lens through which these spaces are valued and utilized. By highlighting how individual and collective values and beliefs influence engagement within these spaces makes a compelling case for the integration of perception and practice as characteristics in BGI planning and management.

To effectively gauge perceptions and practice within a BGI context, corresponding indicators include valued attribute for perception, alongside activities/use and information communication for practices. These indicators, encompassing both normative values and procedural elements, are instrumental in assessing the social acceptance of BGI and yield valuable perspectives on its utilization, management, community interactions and information sharing.

Perception can be both quantitative (e.g., size, greenery) and qualitative (e.g., aesthetics, sociability, quality, and usage) [21]. Practice refers to use and encompasses a range of activities such as walking/jogging, sports, community gardening, restoration, socializing, and participating in community events, common activities in BGI [112]. Alongside activities and information, communication emerges as a distinct practice within BGI, reflecting the nuanced ways communities interact with and value their green spaces [24]. Information communication is often featured as an important component in disaster resilience frameworks [24,53,113] as improved communication and awareness improves the effectiveness of disaster response [24,40]. This practice is also a reflection of a community's values regarding engagement, stewardship, and mutual support [18] and can better enable engagement, learning, and translate human values into action through stewardship [114], which all contribute to improving resilience [115].

Capturing these subjective dimensions is crucial, not only for the development of functional physical BGI spaces, but also for creating environments that align with the cultural and social fabric of the community, thus fostering a resilient and actively engaged community. A graphic illustration summarizing the characteristics and indicators associated with the social values and beliefs dimension is shown in Figure 5.

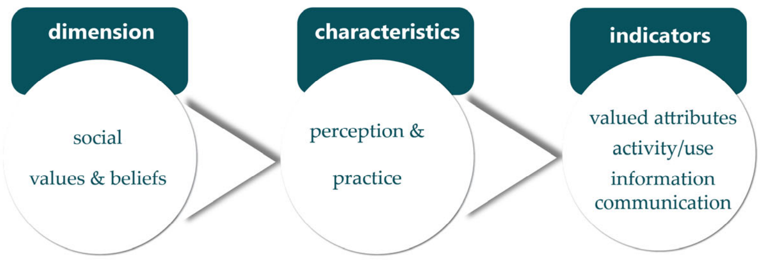

Figure 5. Social values and beliefs characteristics and indicators.

3.3.2. Social Capital

Social capital is a key dimension of social resilience and is widely recognized and studied for its highly influential role [14,24,40]. Social capital refers to the relational networks and trust that exist between individuals and groups of people and the benefits that can be derived from those connections [116]. It encompasses a network of social connections, spanning across individuals and groups, that confer a multitude of invaluable benefits through reciprocity [116]. It holds intangible aspects of trust, norms, and values, as well as tangible resource and connections within social networks [117].

Several studies have revealed that communities with a high social capital adapt, cope, and recover better following a disturbance [28,118–120]. Outside of the disaster context, social capital plays a vital role in building cohesive, healthy, and tolerant communities. This cohesion fosters relationships and trust among diverse communities [13], helping to bridge social divides, enhance cultural competency, stewardship, and learning, all vital component in disaster resilience and social fragmentation mitigation [3,121]. Social networks established through relationships have profound implications for mental health and emotional wellbeing. Socially connected communities share a sense of belonging, which is associated with a greater sense of purpose, identity, and emotional wellbeing [122]. Communities with high social capital often report lower levels of psychological distress and improved coping strategies [123], both important for resilience.

BGI serve as important places where individuals gather, forge connections, and engage in activities that strengthen social networks and bolster capital [18,48]. These areas function as key hubs for social gatherings and various activities that enhance community resilience [124]. Through shared experiences and interactions, BGI spaces facilitate the formation of social networks and foster trust among community members [46]. In the context of BGI, social capital is not only built through the formation of networks but also through how these networks are shared and used for collective benefit. Given the pivotal role BGI spaces play in facilitating gatherings, forging connections, and fostering trust through shared experiences, it becomes evident that the fundamental characteristics of social capital within this context are connections and engagement. These elements are integral to the way BGI spaces cultivate community ties and encourage active involvement, effectively knitting the community's social fabric to ensure it remains vibrant and responsive to its members' needs.

This understanding prompts a deeper investigation into which indicators are most salient at the community level within BGI and necessitates a closer examination of the defining attributes of each. Reflecting on Putnam's [116] foundational definition, which includes 'relational networks and trust', along with the 'benefits accruing from such connections', such as social cohesion, a distinct correlation emerges within the BGI contexts. To build on these concepts, the primary indicators for 'connections' are identified as networks, trust, and reciprocity, while participation and social cohesion are selected for 'engagement'. These indicators are pivotal in detailing how BGI spaces cultivate community ties and promote active involvement.

Networks, trust, and reciprocity serve as foundational indicators of social connections within communities, illustrating the depth and quality of interpersonal relationships that form the backbone of social capital [64]. Social networks are defined by the strength, diversity, frequency, and duration of connections within a social system [125]. Trust serves as the foundation for enabling cooperative action, while reciprocity emerges as the mutual exchange of support and assistance among community members, with both aspects being mutually reinforcing [24].

Participation and social cohesion are critical indicators of community engagement, highlighting the active involvement and unity within communities. Participation illustrates the degree to which individuals contribute to and involve themselves in community activities, reflecting their commitment to communal goals and the BGI spaces that facilitate such interactions [18,126]. Social cohesion is a multifaceted concept that is used to characterize the social environment [46], often referring to the degree of social connectedness and solidarity [127]. Social cohesion relates to positive social interactions [46], and can invite a sense of belonging [128], community, and a level of cooperation within a community [129].

These indicators are also used in various studies [21,130,131] and are integral to renowned tools for measuring social capital, such as the World Bank SC-IQ, Social Capital Community Benchmark Survey (SCCBS), European Social Survey (ESS), and the Australian Bureau of Statistics (ABS) Social Capital Framework. A graphic illustration summarizing the characteristics and indicators associated with the social capital dimension is shown in Figure 6.

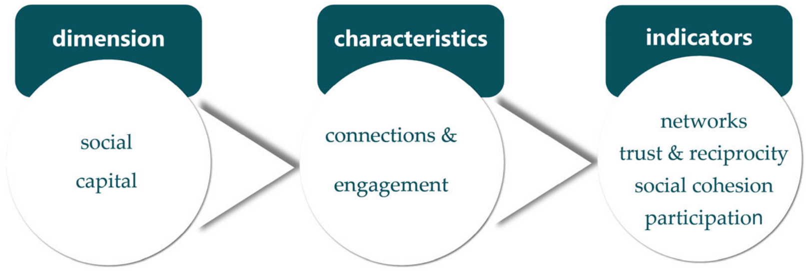

Figure 6. Social capital characteristics and indicators.

3.3.3. Social Structure

Social structure is broadly defined as referring to networks, relationships, and population composition and distribution [132]. Within the 5S framework, social structure is defined as the distribution and composition of a population within a geographic space with parameters such as age, gender, cultural backgrounds, and socio-economics [24]. It includes aspects like demographics and socio-economic stratification and the diverse functions people fulfil within a community, including education, recreation, social interactions, and mobility. This definition provides the basis for place-based and contextual analysis, offering insights about the individuals residing in and engaging with a specific area. It facilitates the creation of a vision informed by demographic realities and ensures that the unique needs of the served population are adequately addressed [133].

In the field of resilience, factors such as population growth, inequity, human mobility, and development in areas prone to hazards are identified as critical elements that influence resilience [14,28,134,135]. Within this context, social structure components of demographics and mobility are pivotal, particularly in addressing challenges associated with urbanization and climate change. These challenges disproportionately affect socially vulnerable groups, including those with lower income, dependent children, older adults, and individuals with disabilities, underscoring a regressive impact [2,4].

Within the 5S framework, key characteristics underpinning resilience include social demographics and mobility [24]. Social demographics encompasses the spatial composition, density, and profile of the population, focusing on specific community needs [24]. Mobility encompasses both long-term aspects such as home ownership and migration, and short-term elements like accessibility to transportation and street connectivity [24].

In the BGI context, understanding social structure is key to identifying the makeup of communities and promoting equitable access tailored to the specific requirements of various demographic segments. This is particularly important in terms of mobility where aspects like walkability affects the immediate access to BGI spaces and influences the frequency of their use, which is crucial for prompting regular engagement and sustained participation [136]. Groups like older adults, women, children, and individuals with disabilities, who face heightened safety and accessibility challenges, are notably more vulnerable to adverse health outcomes [137–139]. Consequently, the United Nations' Sustainable Development Goal 11.7 underscores the importance of establishing green spaces that are safe, inclusive, and accessible, aiming to counteract the disparities in greenspace access experienced by these vulnerable populations [140].

The characteristics outlined in the 5S framework, demographics and walkability are particularly well-suited for use in the BGI context because they directly address the complexities of urban systems. This tailored approach ensures that BGI spaces are not only accessible but are also responsive to the unique needs of various community members. By integrating demographic data and prioritizing walkability, planners can more effectively design BGI spaces that enhance social resilience and community wellbeing. This detailed planning allows for a nuanced response to the community's needs, ensuring that green spaces serve as vital resources for enhancing community resilience and promoting active, inclusive participation.

Indicators of demographics and walkability need to capture the spatial composition and functionality of physical space to align with the broader goals of social structure and resiliency. Demographic indicators include general population profile data and their geographic location, ensuring that vulnerable communities with specific needs such as lower-income groups, families with dependent children, older adults, women, and people with disabilities [2,4] are represented. Walkability indicators, such as walking scores, offer a quantitative measure of an area's pedestrian-friendliness, incorporating factors like pedestrian shed (the availability of foot infrastructure and walking distance), topography, and safety considerations, both from personal and traffic perspectives [141]. These indicators not only reflect the physical attributes of an environment but also its suitability for pedestrian use, directly impacting the mobility of the community members, especially those from vulnerable groups. A graphic illustration summarizing the characteristics and indicators associated with the social structure dimension is shown in Figure 7.

Figure 7. Social structure characteristics and indicators.

3.3.4. Social Equity

For a community to achieve social resilience and an enhanced quality of life, it is essential that there is an equitable distribution of societal benefits and challenges [142]. This approach aims to ensure that all community members have access to the necessary resources to meet their fundamental needs [24,143]. At the core of social resilience is the concept of social equity, defined as the equitable, just, and fair administration of public institutions, including the provision of services, the development of policies, and the allocation of resources [144,145]. Applying principles of social equity is crucial for building resilient societies where fairness and justice are fundamental to collective wellbeing. This approach ensures that resilience involves not only recovery and adaptation, but also inclusive growth and equitable progress.

Urban resilience and inclusivity are hindered by deep-rooted inequalities, with stressors associated with climate change and disasters falling disproportionately on poor and disadvantaged communities, including people of color, those with disabilities, and women, who often lack access to vital services and infrastructure. These spatial, social, and economic divides limit cities' abilities to withstand and recover from adversities, emphasizing the urgent need for addressing these disparities [65,146]. There are numerous initiatives focused on promoting resilience and equity through various programs and initiatives aimed at supporting sustainable urban development and disaster risk reduction globally [147,148].

Many cities are experiencing environmental degradation and social inequity, and are turning to BGI to enhance resilience and improve health, wellbeing, and livability [147–149]. Despite the increasing recognition of the benefits of BGI, there is a notable decline in greenspace per capita in many urban areas [150,151]. Where greenspace exists, its distribution frequently lacks equity [152], with disparities in access and the extent of available space often aligned with differences in income, race, ethnicity, age, gender, and disability [153–155].

For BGI to contribute effectively and equitably to social resilience, these spaces must be designed and managed to be inclusive, ensuring accessibility, safety, and relevance to the diverse needs and preferences of the entire community, most importantly the vulnerable and under-represented groups [156,157]. The fair access and inclusion of these spaces is recognized as a social justice issue [154] because BGI plays an essential role in health and resilience [46]. Studies have shown that communities with greater access to green space report better health outcomes [46], with many of these outcomes associated with social support and increased interaction with others [46]. However, the communities most in need of such access [158] are often less likely to live near BGI [153,159] and may lack the resources necessary to travel there [160]. The absence of fair access and inclusiveness leads to a significant grasp in the benefits BGI can offer [161]. This disparity underscores the necessity of treating fair access and inclusiveness as critical indicators of social equity within the new BGI framework.

Fair access involves ensuring the availability of fundamental needs and basic services, including health and wellbeing [24]. Inclusiveness involves enhancing access to societal participation and resources, particularly for disadvantaged individuals aiming to improve their opportunities [162]. Indicators that effectively measure fair access and inclusiveness include size, distribution, and the use type of BGI spaces. These indicators ensure that BGI meets the diverse needs of all community segments, which is essential for informed sustainable urban planning [163].

Size and distribution metrics, commonly utilized in various public health [164–166] and urban planning [66,167,168] studies, are crucial because they directly impact who can access these spaces and how they are used. Size is indicative not only of the presence of BGI, but also of whether it is substantial enough to facilitate diverse activities, enhancing its usability. These metrics, along with how BGI are distributed across different areas, play a key role in assessing equitable access to these resources. Such metrics for assessing equity allocation are also endorsed by the European Union (Brussels, Belgium), United Nations (New York, NY, USA), United States, and the World Health Organization (Geneva, Switzerland), affirming their relevance in urban planning and public health contexts [169].

The characterization of BGI through a detailed description and classification of amenities and use types plays a vital role in understanding and promoting inclusivity. The presence of BGI does not inherently ensure its usability for diverse groups, underscoring the importance of evaluating how parks meet the diverse needs of the community [81,106]. This indicator serves as an inventory tool to understand the diversity within BGI to ensure that these spaces are suitable and beneficial to all segments of the population.

A graphic illustration summarizing the characteristics and indicators associated with the social equity dimension is shown in Figure 8.

Figure 8. Social equity characteristics and indicators.

4. Development of the BGI Social Resilience Framework

4.1. Introduction and Conceptual Groundwork for the BGI Framework

The BGI Social Resilience Framework, as depicted in Figure 9, represents a novel approach to fostering social resilience through urban blue-green infrastructure. The framework builds upon of Saja et al. [24] and the practitioner framework of by Kwok et al. [20], enriched through a comprehensive synthesis of the existing literature (Phase 1). The new framework intricately weaves together important BGI characteristics and indicators (Phase 2), while addressing the challenges and complexities outlined in Phase 1. Ultimately, the BGI Social Resilience Framework offers a customized blueprint for enhancing urban social resilience through the strategic application of BGI.

Figure 9. BGI Social Resilience Framework.

The BGI Social Resilience Framework's structural architecture is founded on the 5S framework's [24] three-tiered approach of dimensions, characteristics, and indicators. However, it expands upon this model's structure by establishing connections between the dimensions to enhance the framework's robustness and depth. These relationships facilitate the introduction of a fourth tier dedicated to guiding measurement methodologies, thereby enhancing the framework's applicability in BGI. The BGI Social Resilience Framework aligns with the practitioner framework's structural (physical) and cognitive (values) conceptualization and its emphasis on the subjective dimensions.

The BGI Social Resilience Framework is inherently adaptable, featuring context-specific indicators, ensuring relevance and applicability across diverse urban settings and demographics. These indicators reflect BGI attributes that are subjective, such as preferred practices and perceptions specific to people across a range of demographics. The indicators are also spatial capturing BGI distribution, accessibility, and safety within communities to assess equity. This contextual adaptability allows the framework to address the subtilities of place and community dynamics, providing a nuanced assessment of the contributions of BGI to social resilience. It also helps to clarify the concept by anchoring it in specific, measurable terms specifically applicable to BGI, thereby reducing ambiguity. By capturing diverse preferences and spatial equity, the framework is tailored to help understand the diverse needs of communities, enabling it to provide targeted insights for robust resilience urban planning.

The BGI Social Resilience Framework stands apart in its specificity to the BGI context and its community-centric scale, emphasizing not just the physicality and connectivity of spaces, but also the interplay of community values, practices, and the demographics of those who engage with these spaces. Unlike these influencing frameworks, the BGI Social

Resilience Framework moves beyond a disaster-centric view with a stronger emphasis on broader concepts of resilience such as sustainability and wellbeing, reflecting the inherent social advantages of BGI. By encompassing a broad scope of resilience that includes proactive community wellbeing, the framework prepares communities with the necessary tools and capabilities, ensuring that when challenges or disturbances arise, they possess the resilience to withstand and recover effectively, covering the entire disturbance cycle.

4.2. Synthesizing Concepts, Application Contexts, and Measurement Types

4.2.1. Conceptualization

The BGI Social Resilience Framework is constructed around the cognitive and structural elements relating to social systems. Although other conceptualizations identified in the literature exist, the BGI Social Resilience Framework encompasses structural and cognitive characteristics to bridge the gap between the tangible aspects of BGI and the community's perceptions and engagements with these spaces. This approach clarifies the impact of BGI on social resilience. Specifically, this approach underscores the importance of integrating the organic complexity of the physical environment with the social fabric needed to foster community resilience.

Within the BGI Social Resilience Framework, structural characteristics pertain to demographics and walkability and fair access and inclusiveness. These characteristics are quantifiable and relate to the physical characteristics of BGI. These dimensions are critical for the practical support of a community's resilience and support the measurement of tangible elements such as BGI resource size, distribution, and access. This framework's cognitive characteristics, perception and practice and connections and engagement, provide insights into how communities interact with and value BGI. These characteristics enhance understanding of social trust, community engagement, and place attachment, which are key elements essential for the social cohesion and collective efficacy required for a community to thrive.

Additional attributes from the other conceptualizations identified in the literature review are incorporated into the BGI Social Resilience Framework. This framework integrates capital-based and socially interconnected dimensions, acknowledging them as fundamental to social resilience. While it does not quantify coping, adaptation, and transformation directly, these processes are inherently captured within the social capital, values, and equity dimensions, all of which are recognized as crucial for resilience. [28,118–120]. Furthermore, the framework emphasizes the critical role of social relationships and practices in facilitating integration across diverse communities, thereby reinforcing the significance of these social ties in the overarching story of community resilience.

4.2.2. Application Context

The BGI Social Resilience Framework specifically targets the urban context, prioritizing community-level resilience as its primary focus because BGI inherently serves as a communal space. The framework's scope extends from disaster-centric issues to include broader concepts of resilience, such as sustainability and wellbeing, emphasizing the social benefits inherent in BGI. The framework prioritizes an understanding of how the values of BGI and perceptions of BGI correlate with aspects of community life, such as social capital, over assessing the role of BGI in enhancing skills and preparedness for risk management or facilitating community decision-making processes, often highlighted in disaster-oriented frameworks [20,24,27]. Additionally, it focuses on equity in accessing BGI as a continuous asset for sustainable health and wellbeing rather than as a resource allocated post-disaster or as a temporary mobilization space [170–172]. Consequently, this framework addresses the broader challenges of urbanization, climate change, and social fragmentation with a more comprehensive approach to understanding social resilience in BGI.

4.2.3. Measurement Type

The BGI Social Resilience Framework utilizes an indicator method for measuring social resilience. This method is most used in social resilience frameworks [27,61] and is the preferred approach of agencies and practitioners [24]. The indicator method is best suited for measuring the attributes and understanding the inter-relationships between dimensions identified in the new framework.

The indicators within the framework are categorized to align with those outlined in the literature: outcome, process, and normative [24,68]. The diversity of indicators within the framework reflects a versatile methodology that can adapt to the specificities of different BGI contexts. This adaptability is crucial for the framework's applicability in diverse urban settings, enabling it to provide actionable insights into the inter-relationships between BGI features and social resilience dynamics.

The specific roles and contributions of each indicator category within the new framework are outlined below:

- Outcome indicators directly measure the attributes of BGI that are of practical significance to the community. The pedestrian shed serves as an indicator, characterized by the presence of pedestrian infrastructure and the walking distance required to reach BGI. Alongside this, the safety indicator evaluates the security conditions along the walking routes to BGI, focusing on aspects that contribute to community well-being. Additionally, the topography indicator documents the physical features of the landscape, which influence the usability and accessibility of these paths. Size, distribution, and use type are the indicators that gauge equitable access to BGI and ensure it effectively serves the community. Coupled with these, the population profile provides demographic insights that are essential for targeted enhancements in BGI planning, allowing for a comprehensive assessment of equity.
- Process indicators observe the ongoing interactions within BGI, offering a window into the active engagement and social processes that BGI facilitates. These indicators include networks that reflect social interconnections, trust and reciprocity which indicate the strength of community relationships, social cohesion, which measures community unity, and participation which quantifies the level of community involvement in BGI activities.
- Normative indicators reflect the community's values, guiding BGI engagement. Valued attributes serve as a key indicator, highlighting how BGI aligns with the community's core values and preferences. Practice/use metrics reveal the alignment of BGI with cultural and lifestyle values, while information communication assesses engagement in knowledge exchange. These indicators embody the community's ethos, informing BGI policies and practices that resonate with their shared vision for a resilient society.

4.2.4. Summary

Table 2 delineates the incorporation of various conceptualizations and methodologies into the BGI Social Resilience Framework. It summarizes the justification of the selection of the specific conceptual and methodological elements that were selected, detailing their relevance and applicability in the BGI context. Furthermore, the table indicates the foundational and influential sources from the literature review, including the 5S and practitioner frameworks, that are instrumental in shaping the dimensions of the newly developed BGI Social Resilience Framework. This table serves as a bridge, articulating how established frameworks and new insights from the literature have converged to form the underpinnings of the BGI-focused approach to social resilience.

Table 2. BGI Social Resilience Framework Literature Review Integration.

Dimension		**Justification/How**	**Framework References**
Conceptualization	Structural and cognitive (primary)	Integrates physical BGI aspects with community perception and engagement, enhancing social resilience understanding.	Practitioner framework
	Coping, adaptive, transformation (inherent)	These are implicit within the social capital, values, and equity, acknowledged as essential for a community's ability to cope, adapt, and transform.	Literature frameworks
	Social and interconnected (inherent)	Highlights the importance of social relationships through shared values and practice/use for diverse community integration.	Literature, 5S frameworks
	Capital based (included)	Recognized as a key dimension for understanding social resilience.	Literature, 5S frameworks
Context	Hazard specific	Broad and not limited to specific hazards, allowing for a wider application.	N/A (new BGI contextual framework)
	Geographical context	Focused on urban BGI and role in its resilience.	
	Hierarchical scale	Community-level resilience is the primary scale of interest.	
Assessment type	Indicator	Preferred method in social resilience frameworks and by practitioners; suitable for understanding inter-relationships and the attributes of BGI.	Literature frameworks
Indicator type	Outcome	Measures the direct attributes of BGI that significantly impact equitable access. These indicators provide tangible evidence of the fair and the practical utilization of BGI.	Literature, 5S, practitioner frameworks
	Process	Captures dynamic interactions and ongoing engagements within BGI spaces. These indicators reflect the social processes that result from the use of BGI spaces.	Literature, 5S, practitioner frameworks
	Normative	Aligns BGI with societal preferences, ensuring that the framework accounts for community values and aspirations.	Practitioner framework

4.3. Integrating Tools and Insights through Methodologies

In their subsequent study, Saja et al. [61] emphasize the importance of identifying specific tools for measuring resilience indicators, introducing an additional tier in the BGI Social Resilience Framework organizational structure. This fourth tier encompasses diverse methodological approaches that elucidate the tangible and intangible social dimensions of BGI. This expanded framework employs qualitative and quantitative methods to understand community interactions and physical infrastructure of BGI. Through this mixed methodological approach, the framework offers a robust mechanism for evaluating the role of BGI in fostering social resilience, combining the depth of qualitative insights with the precision of quantitative spatial analysis.

In the qualitative domain, characteristics and indicators tied to social values and social capital capture the subjective experiences of individuals. Surveys are particularly valuable in this regard, providing a direct avenue for gathering nuanced insights into perceptions, preferences, and practices within BGI spaces [21,98,173]. These tools enable qualitative data collection, offering a window into how community members engage with and value their green spaces, thereby contributing to a comprehensive understanding of the impact of BGI on social resilience. This perspective aligns with the view of parks and green spaces as cultural landscapes co-created by their users, stewards, and 'ecosystem engineers', highlighting the reciprocal relationship between communities and their environment and the importance of recognizing these spaces as dynamic and participatory realms of social resilience [174,175].

In contrast, the quantitative aspect of the methodology focuses on the spatial and physical characteristics of BGI, employing Geographic Information Systems (GIS) to analyze data on the size, distribution, and accessibility of these spaces. GIS-based methods are often used to facilitate a systematic and objective measurement of BGI attributes within a spatial context [102,176–178].This spatial approach is critical for sustainable urban planning, allowing for the visualization of BGI distribution across different community areas to identify areas of inequity and guide targeted interventions to ensure equitable access to BGI for all community members.

The integration of qualitative insights with quantitative spatial analysis underscores the framework's adaptability and practical applicability. By offering a variety of methodological tools, the framework accommodates the complexity of human–nature interactions within BGI spaces, facilitating empirical research that can guide urban planners in creating spaces that are both equitably accessible to the community and reflective of community-driven values and needs.

4.4. Synthesizing Theory and Practice

The emergent discourse on BGI and social resilience presents a unique opportunity to craft a nuanced operational framework to better understand social resilience. In addition to the absence of unified frameworks outlined by Saja et al. [24], social resilience frameworks remain highly theoretical, expansive, and contextually broad for direct case study application. Therefore, frameworks generally remain largely untested in empirical settings [61]. Conversely, there is need to better integrate theoretical concepts and social system knowledge and the concept of social resilience into the practice of urban planners and managers [179].

While general social resilience frameworks predominantly remain within the realm of theory, a significant body of case study research has focused on the operationalizing aspects of social resilience dimensions (such as capital, values, structure, and equity), specifically in the context of urban green spaces. These case studies underline the applicability of methods to operationalize the framework and emphasize the pertinence and specificity of the characteristics and indicators within the BGI Social Resilience Framework. Key case study examples that support framework attributes and methods include:

1. Survey studies to decipher subjective aspects of community engagement in greenspaces that support social relationships:
    - Investigations into the correlation between perceptions of park attributes such as safety, walkability, sociability, and human activities, and their influence on social capital [21,180]
    - Analysis of the engagement types and social values facilitated by green spaces, showcasing the range and diversity of social activities, and the relationship between social connectivity, the sociability of spaces, and their usage [179,181].
2. Geographic Information Systems (GIS) models that evaluate physical and spatial relationships to understand equitable access to greenspace:
    - Investigation of walkability and pedestrian accessibility of greenspaces using variables such as slope, distance, safety, and the presence of pedestrian infrastructure [182,183].
    - Analysis of greenspace size, distribution, and their alignment with demographic profiles to assess equitable access [184,185].

These case studies, grounded in empirical research, serve to validate the relevance of characteristics and indicators outlined in the BGI Social Resilience Framework and offer detailed methods for testing the framework in a case study setting.

In subsequent research, the BGI Social Resilience Framework is slated for empirical evaluation in Pōneke Wellington, Aotearoa New Zealand. Utilizing GIS spatial analysis, combined with social surveys, the methodology is designed to scrutinize both the equitable distribution and accessibility of BGI and detailed community perceptions and relationships regarding the utility of these spaces. This validation process aims to confirm the framework's utility in an authentic urban environment and contributes to the discourse on equitable BGI development. Ultimately, the goal of this research is to demonstrate how BGI can be customized to enhance social resilience within varied community landscapes, thereby informing sustainable urban development strategies that emphasize inclusivity and the wellbeing of the community.

Empirical insights from this research, underpinned by a comprehensive theoretical framework, offer urban planners' essential knowledge for incorporating BGI to enhance social resilience effectively. Through the application of this framework, planners can discern demographic preferences regarding BGI and evaluate the spatial accessibility of these spaces across various community segments. This methodical approach facilitates the equitable distribution of BGI, ensuring that planning and implementation address the diverse needs and preferences of different demographics, thus contributing to a more inclusive urban development.

5. Conclusions

The BGI Social Resilience Framework addresses the existing gap in the understanding and application of social resilience within BGI contexts while broadening the scope beyond a mere disaster perspective of resilience. It proposes a resilience approach where communities progress toward a more robust and interconnected future, leveraging studies that highlight the importance of social connections and the interaction between the physical structures of BGI and the community's dynamic social landscape. It champions community unity, collaboration, and fairness, all of which are pivotal for communities to effectively manage, adapt, and innovate in the face of adversities [102,176–178].

The framework aligns with and actively supports UN SDG 11's vision for cities that are inclusive, safe, sustainable, and resilient, showcasing a forward-thinking approach to where and how urban development unfolds. Specifically, it directly addresses goal SDG 11.7, emphasizing the importance of providing safe, inclusive, and accessible green and public spaces. Indicators for this goal include the extent of green space, removing barriers to access, and increasing the number of people from different demographic groups, most notably women, children, older people, and people with disabilities accessing these spaces. This initiative serves as a pivotal step towards creating urban spaces that genuinely cater to the needs and wellbeing of all community members, setting a new standard for urban resilience and inclusivity.

The BGI Social Resilience Framework distinguishes itself by offering a comprehensive approach that merges strategic urban infrastructure planning with community social fabrics that reflect the unique characteristics and needs of communities. This forward-looking approach supports empirical research to ensure equitable and context-sensitive enhancement of social resilience, fundamentally incorporating it into urban life. By enabling urban planners to operationalize its methodologies, the framework aims to strategically enhance urban resilience by ensuring equitable access to BGI, an essential element for a city's resilience profile. It combines the physical and social dimensions of urban development, advocating for an integrated planning approach that prioritizes social wellbeing and environmental sustainability. Through its application, the framework assists in fostering resilient, inclusive, and adaptable urban environments, thereby reinforcing the vitality and sustainability of cities.

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Maintaining Community Resilience through Urban Renewal Processes Using Architectural and Planning Guidelines

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Abstract: The article deals with community resilience-oriented urban renewal in a geographical periphery, and the characteristic patterns of public housing built in the 1950s and 1960s. When the existing fabric is well-established and effectively serves the residents, demolition and redevelopment may not be the most strategic approach if they undermine the internal resilience of public housing based on functionality. The article addresses the question of how to add new construction and a new population to these patterns of public housing in the periphery without affecting the community resilience of longtime residents and the sense of urban vitality and innovation of the new population. In order to address this question, we examined the built environment's qualities in relation to the population's resilience. Specifically, we conducted a quality analysis of the built environment focusing primarily on walkability and connectivity, diversity and land uses, open public spaces, and visibility to internal and external views. The findings of the analysis recommend developing a multiple urban spatial network relying on the longtime community's resilience and a new spatial network for the newcomers. This is a potentially win–win solution. The old neighborhoods remain, while at the same time an additional layer of housing and other land uses will be developed along the edges of existing neighborhoods. The proposed analysis will be demonstrated on the peripherical city of Kiryat Yam.

Keywords: community resilience; public housing; periphery; architectural guidelines; urban design guidelines; urban evaluation; urban analysis; the case study of Kiryat Yam

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1. Introduction

This article addresses spatial aspects in urban renewal, so that they do not negatively affect the existing community resilience but enhance it. It examines how community resilience is defined, whether aspects related to the quality of the built environment contribute to it, whether there is a unique type of community resilience in sociogeographically peripheral locations, and what physical–spatial guidelines for renewal in peripheral areas are capable of enhancing community resilience.

The literature on urban resilience has grown out of the increasing research attention to sustainability [1]. Beyond cities' ability to deal with physical hazards such as floods, rising sea levels, earthquakes or fires, planners and researchers have realized that a sustainable town or neighborhood also needs managerial and socioeconomic strengths. Accordingly, planners have included under the definition of urban resilience knowledge areas that have long been part of city planning [2]. Nevertheless, most studies deal with the relationship between resilience and sustainability, i.e., a city's ability to deal with physical disasters [3], so that studies that offer physical solutions tend to focus on the ability to sustain engineering capabilities in emergencies.

Since this article discusses spatial outlines, the question is whether there are guidelines for physical urban planning that provide multidimensional resilience, that is, support urban resilience to changes over time, both physical and communal. Feliciotti et al., (2017) [4] found that the structural principles of premodernist cities are better able to deal with changes, and therefore provide greater resilience. The small plots, the divided ownerships, and the dense grids of passages are more flexible than the huge plots with limited passages in modernist cities. This division into smaller fragments enables us to find functional alternatives for failing areas, transportation bypasses, and the flexibility required to contain changes over time. According to Feliciotti et al., unsurprisingly, urban outlines that have evolved over centuries while dealing with changes provide greater resilience than conceptual principles based on theory, such as the modernist urban outlines.

In geographical peripheries, a sense of community is one of the most important aspects of resilience. On the global scale, neoliberalism, globalization, and technologies have been found to damage urban resilience, while community feeling enhances resilience to changes and even disasters [5]. Su et al., (2022) [6] found that in urban areas, resilience relies on the socioeconomic structure, whereas in peripheral areas, it relies on traditional knowledge and economic independence. Adam-Hernández and Harteisen (2020) [7] argued that peripheral communities have a strong potential for resilience, being flexible psychologically, ecologically, and socially. In this sense, it may be argued that in the periphery, the urban–morphological flexibility mentioned above as characteristic of resilience is translated into economic and community resilience. Accordingly, their findings suggest that in communities of this kind, categories of resilience found in the literature should be adjusted to the local situation of the residents, rather than imposed in a top-down way.

In Israel, many neighborhoods, now earmarked for renewal due to the aging of the houses and populations, have been built by the Ministry of Housing. As such, they embody ideologies with regard to desirable neighborhood longevity and communal relations. In Israel's two first decades—the 1950s and 1960s—the neighborhoods represented the modernist approach of Gropius's Zeilenbau or La Corbusier's open plan. Both were informed by the basic assumption that life should be lived next to green areas rather than urban spaces. Accordingly, these neighborhoods did not face the streets, but inwards, towards open spaces, which were supposed to be the beating heart of the community and to contribute to its cohesion [8].

The sociogeographically peripheral nature of the old neighborhoods, with their small apartments, has meant they have been left behind, both structurally and socially. Nevertheless, both their initial planning and their remoteness have contributed to their communal resilience. In many neighborhoods, everyone knows everyone, and many feel "at home" in the neighborhood spaces [9]. Accordingly, urban renewal based on destruction and reconstruction can damage one of the key elements of neighborhood resilience—community feeling [10]. In other words, even if the modernist construction is torn down and replaced by a new neighborhood informed by premodernist principles proven to be more resilient to change [4], the neighborhood stands to lose its community resilience, which is so essential in the periphery.

In this study, we address urban renewal in a geographical periphery by acknowledging the potential of strengthening the resilience of the longtime community by enhancing the quality of its spatial areas. At the same time, we recommend developing a new spatial network for newcomers, based on existing urban planning.

Urban Renewal Mechanisms

Urban renewal is defined as the enlivening of a neglected and deteriorated urban area. Often, it involves the injection of a new population and/or new housing units and land uses into such an area [10].

In Israel, urban renewal processes are based on three characteristics, two of which are related to statutory planning procedure and the third to a neoliberal economic approach. The first is the nature of the plans; these are based on zoning regulations (based on land uses) where the planned area and building regulations are divided into zones according to uses such as housing, commerce, and industry [11]. The second characteristic is the planning hierarchy—from national outline plans, through comprehensive urban planning, to a local and detailed outline plan with clearly defined and delineated areas, construction guidelines and limitations, and road development, etc. Each planning level is subordinate to the one above it.

To promote urban planning in Israel, two major approaches may be taken. Some planning is imposed top-down by the state or municipality, and some is initiated bottom-up by the residents but promoted and incentivized by the state. The latter includes the following:

1. Construction and densification: Enlarging existing housing units and buildings by adding rooms or balconies as well as floors. This includes the National Outline Plan (NOP) 38/1, designed to reinforce buildings against earthquakes, which allows adding a floor or two to an existing building.
2. Evacuation–construction, involving the destruction and rebuilding of a building or a compound of buildings and significant densification. This process is promoted by either the municipality or the residents, with the support of an urban renewal administration, and may also be included under the NOP (38/2), such that the newly constructed building includes another floor or two [12].

What all these approaches have in common is the reliance on private capital. As part of the accelerated privatization of the entire Israeli economy, today it is free market entrepreneurs, rather than a state entity such as the Ministry of Housing, that are responsible for new construction. No public or public–private capital is involved—only private funding. Consequently, new construction is initiated only if the renewal ensures profit. The entrepreneurial profit comes from selling new apartments on the free market. Thus, the higher the land value the fewer new apartments have to be built to secure profit. The lower the land value—as in peripheral locations—the more apartments need to be built, hence the higher the housing density in new projects [13].

Consequently, urban renewal is either not implemented in Israel's periphery or only implemented when building ratios are increased to enable new construction that is at least six times as dense as the old. In this type of evacuation–construction process, the new construction projects are made up of high-risers that are foreign to the location and its socially peripheral population [14]. Moreover, the process of destruction and construction and the massive addition of new tenants affects the previous sense of community and erases the outer spaces that used to serve as the community's "home". Thus, they threaten one of the key aspects of resilience in the periphery.

2. Objectives and Methodology

Given the problem of urban renewal in Israel's geographical periphery, we need to ask how community resilience may be sustained in peripheral cities while promoting urban renewal. How can spatial and communal urban renewal, which involves the addition of new populations of higher socioeconomic status, be implemented while improving the urban areas of the built environment? How can this be done without driving the longtime population away, without damaging its community cohesion, and while also improving it? Is there a physical outline that can ensure such results?

The present study builds on the results of Shach-Pinsly and Ganor (2021) [15], who found that different communities living in the same neighborhood use different urban spaces. Each community finds the streets, urban spaces, and uses suitable for it, and resides and moves in and through them, with certain overlaps and interphases with other communities. These serve to enhance the communities' cohesion and resilience. Hence, urban designers and planners should reinforce existing communities in their place and produce new places for new communities. Both communities can continue developing in parallel, together and separately, in the same neighborhoods.

Therefore, to carry out urban renewal in peripheral cities and neighborhoods, the following three steps must be taken:

1. The communal character of the peripheral site earmarked for urban renewal must be substantiated and its special loci identified. Communality will be examined both in terms of its spatial aspect and in terms of the community's content. We will assess

the built environment to see if two populations can live there at the same time, but in different spatial arrangements. The communality analysis is based on 95 interviews conducted with the people of Kiryat Yam in March and April 2020 as part of an urban planning studio [16]. Interviewees were asked about the community of Kiryat Yam, their use of space, and other topics.

2. In order to promote urban renewal, it is necessary to analyze the qualities of the built environment. We argue that certain physical characteristics support high levels of the qualities of the built environment that are also conducive to community resilience and should therefore be incorporated into the urban renewal plan. This will enable both the retention of the longtime population and its communal characteristics, as well as the integration of the new population.

   The qualities of the built environment include such values that can be measured quantitatively, such as population density, number of housing units, distances between buildings or size of open spaces [17]. They also include qualitative values, such as the quality of public space, the diversity of the human and built environment, walkability and urban networks, accessibility and connectivity, the built environment's safety and security, and open vistas and green areas. The current study focuses on (1) walkability and connectivity; (2) urban usages and diversity; (3) the quality of the public open spaces; and (4) the visibility of internal and external views.
3. Through an examination of the city's historical background, we will be able to understand the DNA of its urban planning. We will also examine the existing urban renewal plans to see whether they are compatible with community preservation and environmental quality.

The analysis will be conducted on the peripherical city of Kiryat Yam.

2.1. Qualitative Values of the Built Environment

2.1.1. Quality of Public Space

Gehl (2013) [17] studied human needs in open public spaces in built environments. He found that the number of people and the length of time they spend in the public space attest to its quality. He distinguished between three categories of activity in public spaces: (1) necessary activity that would be carried out regardless of conditions, such as walking to a bus station; (2) unnecessary activity that depends on such factors as the weather and an enabling public space; and (3) interactions with others in the space. Gemzøe (2006) [18] divided urban space's ability to meet human needs into three basic levels: protection, comfort, and enjoyment. The main three "vital" functions of a city space are meeting place, market place, and connection space [19].

In this article, we argue that the existing space in the peripheral neighborhood earmarked for renewal must already provide optimal qualities to its current community, and yet offer enough space to enable the construction of an additional quality space for the new community.

2.1.2. Diversity of the Human and Built Environment

The importance of urban diversity is increasingly appreciated. Florida (2005) [20] created the Composite Diversity Index, which includes three diversity indices: gay, bohemian, and foreign-born. A correlation was found between the presence of LGBT people and economic development and hi-tech industry. This finding lends support to the claim that strengthening a city's demographic diversity and its openness to diverse populations can attract significant human capital. Florida's index uses numerical data, without addressing their interrelations with the city's physical characteristics. Rothschild (2021) [21] studied physical diversity and identified 26 characteristics that can be used to assess it, including housing unit mix, urban block size, degree of mixed uses and density mix. She concluded that the optimal urban mix is a diverse urban mix, in both human and physical terms.

In this article, we argue that the space earmarked for renewal in the peripheral neighborhood must include new construction that differs from the existing one, which is diverse in itself in terms of the abovementioned and other parameters. Diverse construction would be appropriate for the new population and thereby contribute to urban renewal.

2.1.3. Walkability, Accessibility, Connectivity and Urban Networks

Telega et al., (2021) [22] argue that walkability is characteristic of attractive, safe and friendly urban spaces. They present a new approach for measuring walkability, based on density maps of urban land uses and networks of pavements, walking routes, and accessible paths, thus tying zoning together with walkability. Nelessen (1994) [23] divided urban space into three sections, based on walking distances. The first is an average 230 m walk from a private vehicle parking area to a specific destination such as a shop. The second is a 460 m or five minute walk—the optimal distance for a neighborhood. The third is the maximal distance people would be willing to walk frequently to arrive at any destination, which was found to be 800 m. Another study found a significant increase in people's willingness to walk to their destination when it is located within 200 m of their home [24].

Three main aspects of the built environment affect the accessibility and connectivity of space: urban density, urban design and morphology, and diversity [25]. Peponis et al., (2007) [26] found that the relationship between morphological indices of streets and their accessibility can be used for defining and planning urban density in relation to urban accessibility and design. Jayasinghe et al., (2021) [27] presented a model for evaluating urban changes and limitations based on the 3D relationship between density, typological characteristics, zoning, and accessibility in urban areas.

Based on these findings, we argue that the existing space in the peripheral neighborhood earmarked for renewal must already be walkable. In other words, its network of streets and paths must be based on distances of up to 460 m. Furthermore, we argue that in order to retain and reinforce community resilience after urban renewal in peripheral areas, the existing urban network structure must be retained, as it sustains the existing community and can be relied upon to support the integration of the new population as well. Moreover, based on Shach-Pinsly and Ganor (2021) [15], different networks may be planned for different longtime and new populations.

2.1.4. Open Vistas and Green Areas

The added value of open vistas or landscapes visible out of one's window has been studied by various researchers [28]. This contributes to general well-being, whether the landscape is distant or near [29], and even if it is little more than trees and vegetation [30]. Even when distant, a view of the sea adds to the value of a space [31]. This is evident in the prices of assets with nice views [32], and various methods have been developed to measure the amount and direction of visible views [28].

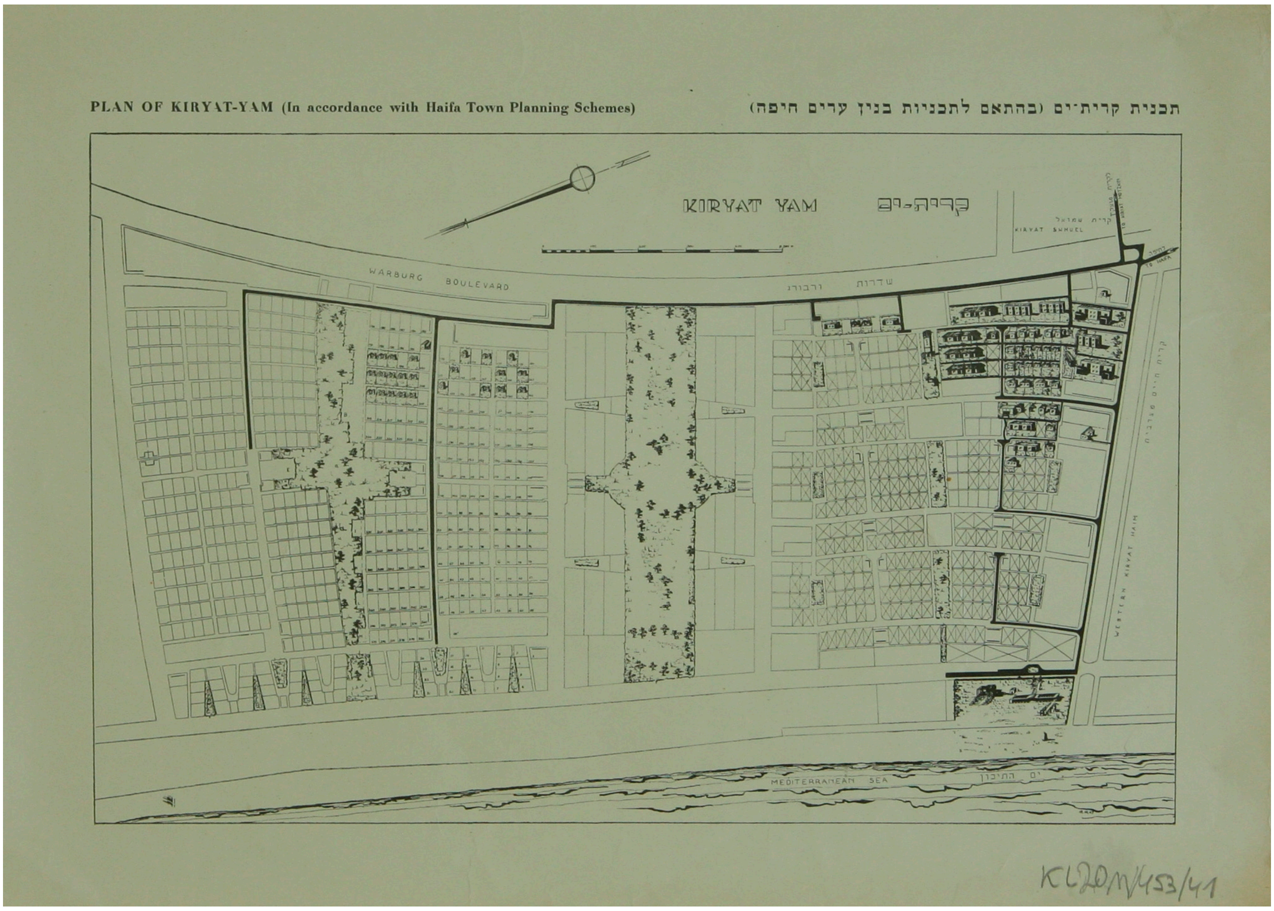
2.2. Case Study: Kiryat Yam

In what follows, we illustrate our analysis and proposal through the case study of a peripheral town in northern Israel—Kiryat Yam ("Sea Town"), located along the Mediterranean Sea. The town benefits from significant community resilience but requires renewal.

It is important to emphasize that the article is theoretical, exploring the topic and proposing an innovative solution that has not yet been tested. Therefore, the data presented are not quantitative. These quantitative data will be collected in a more advanced stage of the research.

Historical Background:

Kiryat Yam is located in the northern part of Israel, between Haifa, the capital of the northern metropolitan area of Israel, and Acre (Figure 1b), which are both old cities situated along the Mediterranean coast and located at both ends of the same bay. Acre is one of the oldest port cities in the world, with its maritime history dating back to the Early Bronze Age. Modern Haifa was founded in the mid-18th century and, starting from the 19th century, developed significantly and left Acre behind. Kiryat Yam serves as the northernmost city in the sequence of medium-sized cities between Haifa and Acre.



a

b

Figure 1. (**a**) Kiryat Yam's plan (**left**) (source: Reprinted/adapted with permission from Ref: Owner, Central Zionist Archives, from the collections of the Central Zionist Archives, Jerusalem; (**b**) Kiryat Yam's location in the north metropolitan area (**right**) (source: https://www.openstreetmap.org/, accessed on 1 November 2023).

Kiryat Yam was planned before Israeli statehood. The land was bought in 1928 by the Jewish National Fund and the East Palestine Corporation [33]. The plan for the new town, 2.5 km long and 1.5 km wide, was drawn by Alexander Klein. Born in Odessa, Klein fled the Russian Revolution and relocated to Berlin in 1920 [34]. There, he developed his small apartment concept—an apartment with no hall and a clear separation between public and private spaces. Finalized after a study of domestic behavior [35], the small apartment embodied his architectural doctrine: planning must be rational and informed by research, in the spirit of modernism.

Based on this rationale, and Klein's European concept of a street hierarchy, the workers' town of Kiryat Yam was planned with a clear separation between housing and leisure uses, with a rational traffic system based on five major avenues leading to the sea, perpendicular to streets and alleys running parallel to the sea. In addition, housing areas were divided equally, including a small patch of land for each housing unit that could also be used for growing vegetables for home consumption. This was influenced by the Zionist ideology, which sought to attach the Jews immigrating to Palestine to the land, as well as increase equality in the spirit of socialism [36,37] (see Figure 1).

Construction began in 1941 but included only a few houses. It was resumed in earnest after Israel became independent in 1948 [33], when Kiryat Yam was built by the state's Department of Public Housing, which would become the Ministry of Construction. In order to house the new immigrant Jews, who tripled Israel's population during its first decade, some of the houses were built not according to the original plan. The identical multi-story buildings were located according to the modernist city building approach, according to Gropius's Zeilenbau or La Corbusier's open plan, facing open areas. Consequently, there was no need for streets and alleys, since walking in this area was supposed to be unimpeded (see Figures 2 and 3).

Figure 2. Free-standing buildings in Kiryat Yam in the 1960s. Source: Reprinted/adapted with permission from Ref: Owner, Central Zionist Archives, from the collections of the Central Zionist Archives, Jerusalem.

Figure 3. Construction plan of central Kiryat Yam, with a color scheme indicating the number of floors, such that most houses have 2–4 floors. The modernist open plan is evident. Source: [38].

Given that the modernist nature of the neighborhood represents public housing and many neighborhoods throughout Europe [39], we found it appropriate to focus the article on this urban fabric.

3. Results: Analysis of the Built Environment—The Community and Spatial Perspectives

3.1. Sense of Community

Kiryat Yam's population has remained stagnant since 1995, with 39,000 residents. Despite the years-long emigration from the town, many of its longtime inhabitants are not interested in leaving. According to the Central Bureau of Statistics (2020) [39], its socioeconomic rating is five out of ten.

Approximately 26% of the population consists of seniors (14% national average), around 21% are children up to the age of 18 (33% national average), and 53% fall into the working-age category (similar to the overall country's percentage). This demographic distribution indicates that the city is predominantly aging. The majority of workers are in a salaried position, with an average salary that is 20% lower than the national average. About 40% of salaried workers earn the minimum wage accepted in Israel, which is 20% lower than the country's average wage. One prominent characteristic of the city is its role as an absorption center, resulting in a diverse population, including people from different origins. Since 1990, 36.5% of the total population are immigrants. Approximately 87% of residents work outside the city, with a notably high daily commuting rate. About 47% of residents commute to work by private car, while there is a significant use of public transportation for commuting to work (Central Bureau of Statistics 2020 [40]).

In March 2020, as part of a city planning studio for graduate students at the Technion—Israel Institute of Technology, we conducted interviews with 95 town dwellers of all neighborhoods, aged 16–73. About 40% had lived in Kiryat Yam for 20–30 years, and the others had lived there for over 30 years [16].

The survey produced three main findings. First, many interviewees were not satisfied with the services in town. About 40% stated they were not satisfied with the educational and sports services. Many pointed to the need to improve the town's visibility and public transportation. Many others complained about the lack of workplaces, forcing many locals to commute. Still others complained about the lack of leisure and commercial centers. One participant wrote that "there's nothing apart for a café".

Second, there were diverse and active social groups in town. These included youth movements, community and family groups (parental patrol, community centers), groups assisting new immigrants and senior citizens, various welfare centers (soup kitchens, occupational/financial assistance) and various community-based media groups.

Third, despite these weaknesses, the residents liked their town and community and were not interested in leaving. About 75% felt safe in town, and 51% liked being close to the sea and being able to access it with ease. Note that Kiryat Yam is exceptional in this regard, as towns adjacent to the sea are usually more expensive and attractive. Finally, 75% expressed their desire to remain in Kiryat Yam, stating that it was quiet, compact, and communal.

The data from the Central Bureau of Statistics (2020) [40] and the analysis of interviews indicate that despite a low level of satisfaction with the current situation in Kiryat Yam and the public services the city offers, a significant majority of residents choose to stay in the city. They rely on additional qualities that the city possesses despite the data, such as tranquility, a sense of security, proximity to the coastline, and more. We see these aspects as a future strength and a bright spot for the city, countering the negative aspects of the deteriorated existing apartments and buildings. As we move forward with urban renewal and redevelopment, it is crucial to rely on these aspects while maintaining the existing community cohesion and strength in the city.

3.2. Analysis of the Quality of the Built Environment

As mentioned, the urban road grid is based on five main avenues leading to the sea. These avenues divide the town into neighborhoods and districts, which in turn are subdivided by streets running perpendicular to the avenues and secondary streets running parallel to them.

The following describes the analysis of the quality of the built environment in terms of the four main characteristics: walkability and connectivity, public open areas, diversity and land uses, and visibility towards the inner and outer views.

Walkability and Connectivity:

The existing urban grid shown in Figure 4 is based on streets and paths connecting the various areas of the city. It contributes to strengthening Kiryat Yam's longtime community. The public open space of the neighborhood is already accessible and adapted to the needs of this population. The residents "own" it, functionally speaking, feel safe in it and consider it a continuation of their domestic uses. The road system is highly dense, with high accessibility; it is well-ordered and walkable, and suitable for all ages [41]. In fact, this is a grid city in the most basic sense. For example, the distances between the inner roads are 50–100 m—highly walkable. Between the large urban blocks, we find distances of 200–300 m—also highly walkable. Because of the sparse construction within and between the neighborhood, both internal neighborhood views and outer urban views of the avenues, and from there to the sea, are highly visible, with the latter in particular being significant for the residents.

Diversity and Urban Usages:

Our analysis of the current situation indicates that the public and commercial areas are planned sparsely and disjointedly, without diversity, and with little in the way of capitalizing on the grid to create a continuous system with connectivity across the various areas along the main avenues. To the extent that there are commercial hubs, they are highly localized, not distributed across the town, and disconnected, thereby failing to optimize the town's potential (see Figure 4). As we have seen, the interviews indicate that there is much to be improved in commercial, cultural, occupational, and public buildings to sustain a diverse, high-quality, and bustling town. For culture, employment, and commerce, the residents of Kiryat Yam have to commute to neighboring cities.

Open Public Areas:

Kiryat Yam was planned disjointedly, without connectivity between the various areas along the main traffic routes (see Figure 4). However, a tour of the neighborhood indicated a wide variety of open public areas between the buildings, and their diverse uses (see Figure 5).

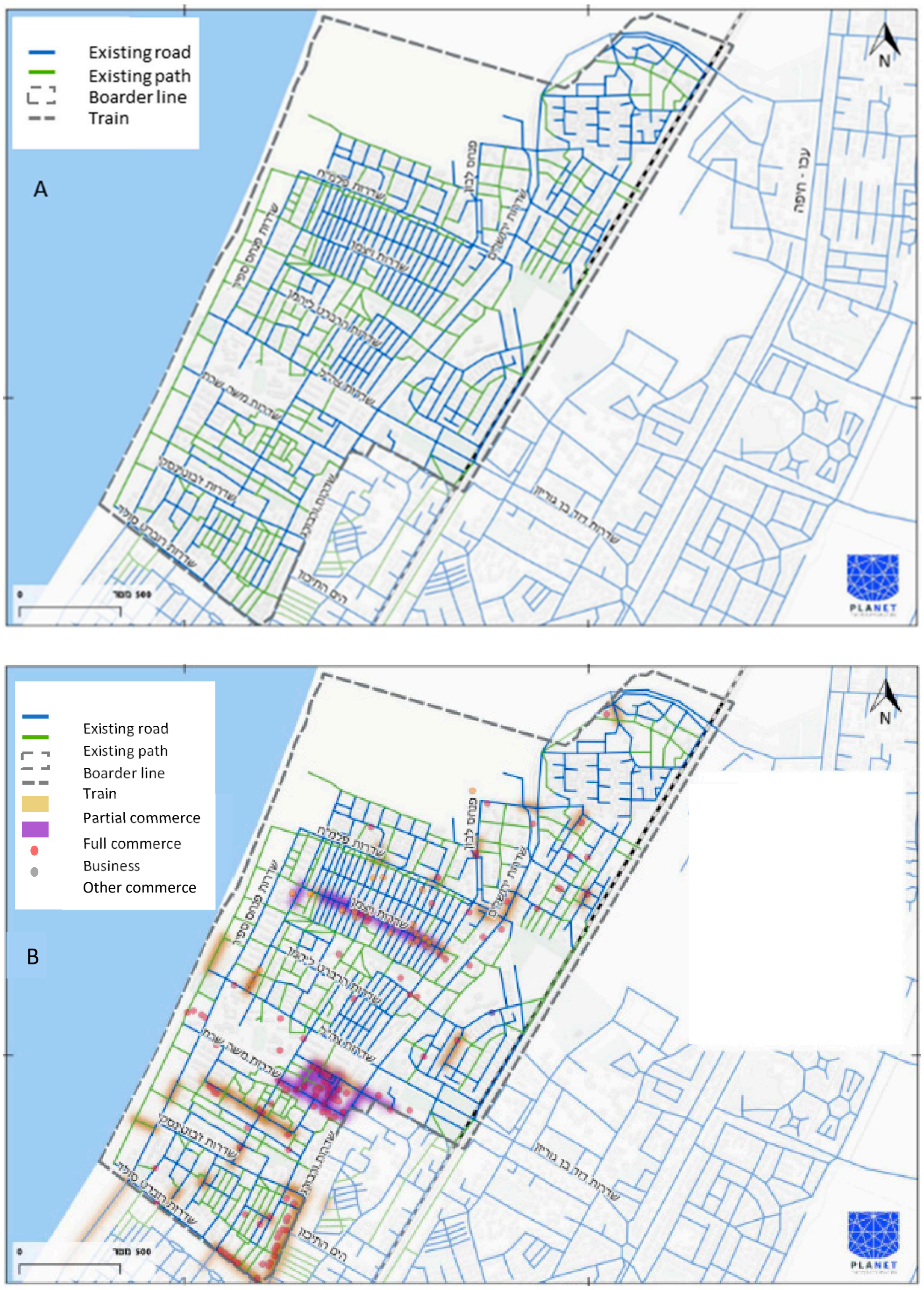


Figure 4. *Cont.*

Figure 4. The advantages and functionality of the urban grid: (**A**) the urban grid; (**B**) dispersion of commercial centers; (**C**) dispersion of public open spaces and centers. Source: [33].

A modernist urban fabric combined with public housing fabric has resulted in a hierarchy-free urban fabric characterized by relatively low-rise buildings (most reaching no higher than four floors) and vast, undefined open spaces. Both the low height and fabric facilitate the connection between interior spaces and external spaces, particularly as the buildings and public open spaces evolve over time. This combination facilitates the development of a sense of ownership towards the various public spaces. Planned urban activities, along with initiatives from the residents, have created pleasant open spaces defined by natural elements that well serve the community's needs, as illustrated in Figure 5.

These areas vary in size, enabling group gatherings of different sizes. Some are small, with chairs, eating areas, play areas and gardens. They are connected by local paths, enabling high connectivity and walkability between the residential areas. A tour in the Jewish holiday of Sukkot (held in October 2023) by the authors demonstrated how these areas could be used to build the communal temporary huts where the holiday is celebrated (see Figure 5A). In different terms, these spaces, fruits of modernist neighborhood planning, serve as meeting points for the old community.

Visibility to the Open Views:

Access to the open views, whether internal or external, is Kiryat Yam's forte. With regard to internal, urban views, the houses look out to the open neighborhood areas, some of which have been developed by the municipality or residents (see Figure 5A–D), and some of which are neglected (Figure 6C). The broad and empty avenues represent another type of open vista, and the sea is obviously an important asset in that regard (see Figure 6).

3.3. The Urban Renewal Plan

Over the years, the buildings erected in the 1950s and 1960s, populated by low-income new immigrants, became aged and deteriorated. Urban renewal plans such as the Comprehensive Urban Outline Plan [40] have sought to demolish the low and sparse constructions in favor of nine-story buildings and high-risers, in order to increase the existing population four- or even five-fold, thus ensuring profit for the private entrepreneurs. Although the guidelines for the comprehensive plan of Kiryat Yam include upgrading the existing street network and prioritizing pedestrians, bicycles and public transportation (in that order), the plan does not address the longtime residents' needs, nor Kiryat Yam's nature as a grid city.

Figure 5. Spatial and human manifestations of community: (**A**) the building of a temporary hut to celebrate Sukkot in a public area attests to the residents' sense of belonging; (**B**) an authentic recreational area on the ground floor of a condominium; (**C**) a neighborly social meeting in a public space; (**D**) a neighborhood playground; (**E**) a system of intraneighborhood paths connects various functions and promotes community feeling; (**F**) the renovation of old buildings indicates that the residents are interested in staying in Kiryat Yam. Photographs by the authors.

Thus, in the detailed masterplan for the urban center (originally planned as a park), derived from the comprehensive plan, only high-risers are planned [38] (see Figure 7). Such construction is unsuitable for a low-income population unable to afford the upkeep. Therefore, either the buildings will be neglected and abandoned by the high-income population, or the low-income population will be unable to afford to live in their own city, and it will be gentrified [42].

Figure 6. Open areas and views: (**A**) very broad avenues leading to the sea, inspired by the modernist planning that prioritizes motorized traffic; (**B**) open view of the sea; (**C**) open inner areas between the buildings, also inspired by modernist planning and the principle of open plan design. Photographs by the authors.

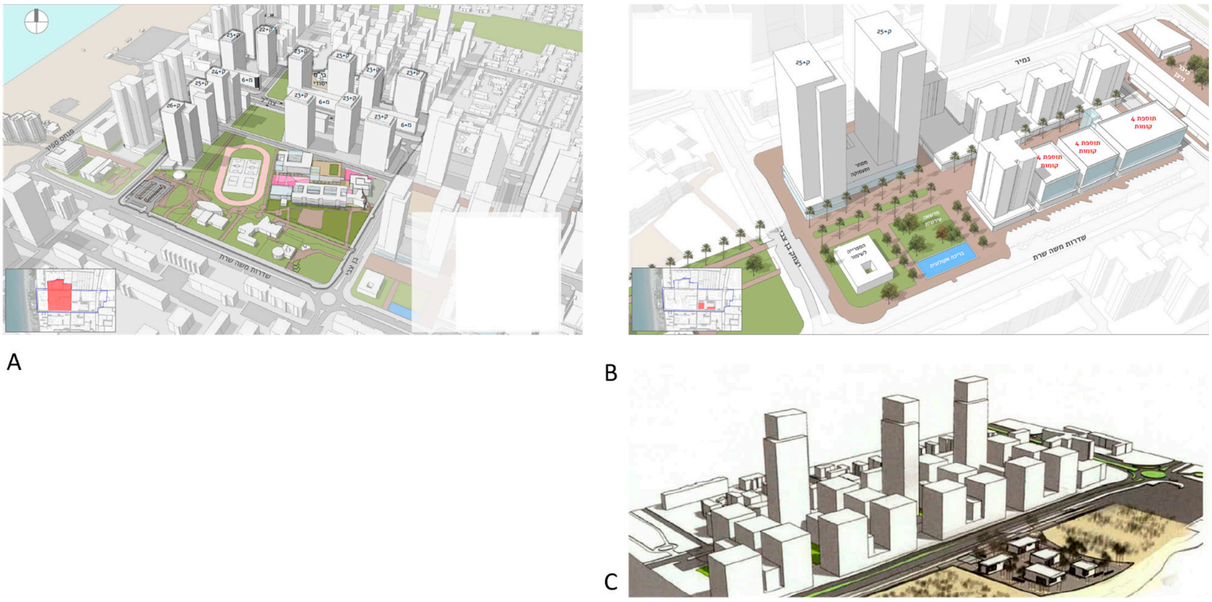


Figure 7. Urban renewal plans: (**A**) high-rise construction in the detailed outline plan; (**B**) the eastern extension of the urban center in the masterplan for renewing the center [38]; (**C**) postevacuation construction of nine-story buildings and high-risers (source: Urban Annex to Outline Plan) [33].

The plan for developing the Cooperative Bloc [43]—an area of public housing from the 1950s at the center of town—suggests that this plan does promote walkability by expanding walking areas (to 87% compared to 62%) as well as the shaded areas (to 41% from 3.5% (see Figure 8)). However, this plan does not promote Kiryat Yam's general renewal and does not change its open public spaces in any significant way, because it does not connect its various parts beyond the specifics detailed in the plan. It concentrates various uses into a single hub, thereby contributing little to strengthening the urban grid. Moreover, it does not connect to the network of public open spaces, nor open up new vistas.

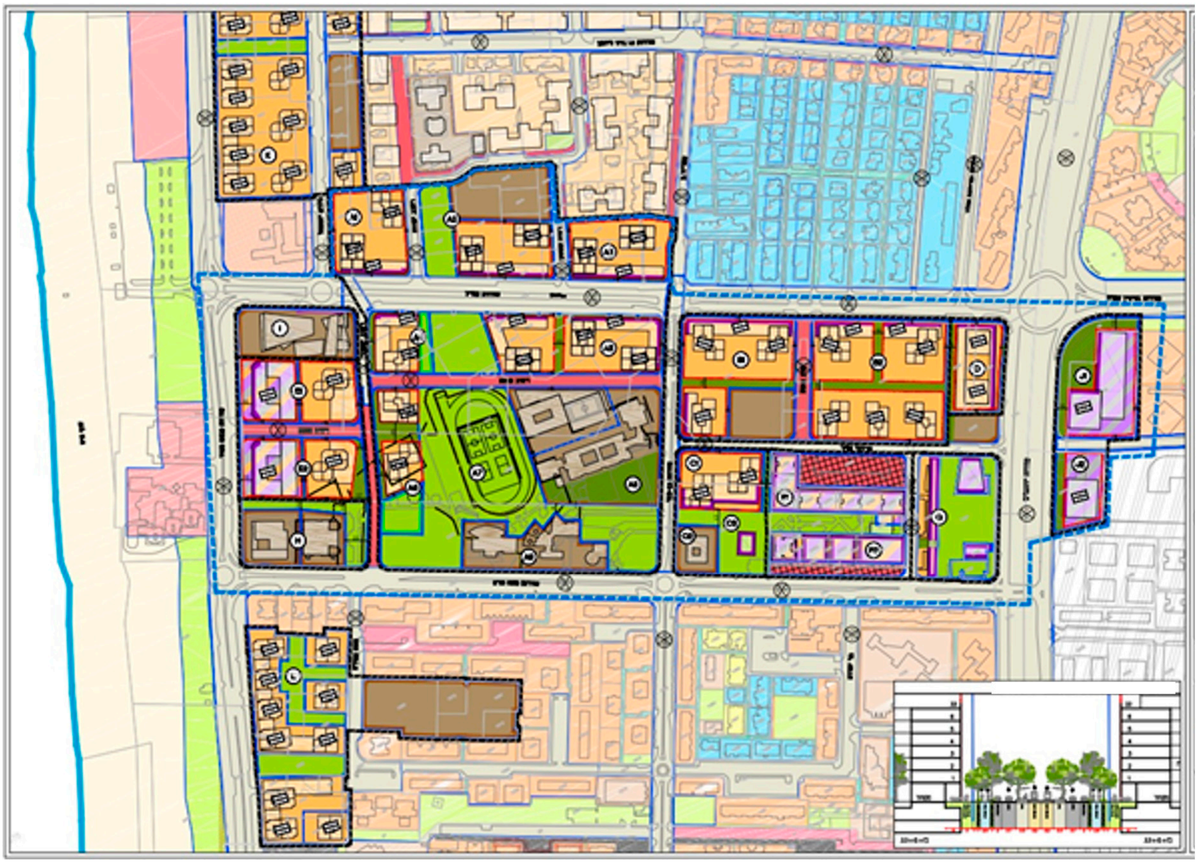


Figure 8. Proposed urban renewal plan—Cooperative Bloc. Source: [38].

To conclude, Kiryat Yam's current sources of community resilience [16] have not been taken into consideration in the renewal plans, which propose complete destruction of the old spaces and buildings. The landscape and community values of the inner-neighborhood open spaces have been neglected as well. Most critically, the urban spatial qualities have been ignored; the walkable grid that enables a distribution of diverse uses, mainly along the avenues. Moreover, the broad avenues offer significant space for additional construction that has not been taken into consideration. Thus, the old urban fabric has been erased, the city has been divided into functional areas (according to the zoning approach), and the planned high-risers are situated in space without regard to the current grid.

3.4. Proposed Urban Renewal Plan

3.4.1. Four Principles

To sustain the existing community and its inner-neighborhood open spaces, and assuming that the conditions detailed in the current study section obtain in Kiryat Yam, our proposal for urban renewal is four pronged.

1. Walkability and accessibility must be reinforced to serve both the longtime and the new community. The overall approach to urban development must return to the "old–new" concept (the urban DNA) of Kiryat Yam: high accessibility and five main avenues leading to the sea. This basic concept naturally promotes urban walkability.
2. Inner-neighborhood areas must be further developed for the longtime residents by cultivation, improved access, and adding a variety of uses; this is based on the

understanding that these spaces constitute the 'home' of the old community, serving its existing and ongoing of functions in the area.

3. The five avenues need to be complemented with open public areas throughout (Figure 6). At present, the plan is for a network of bicycle routes along the avenues. Combined with them, continuous open public spaces connecting the main avenues and public areas between the residential buildings in the old neighborhoods will contribute immensely to the city's public areas.
4. The views to the open areas must be used to construct the edges of the avenues, add varied uses, strengthen the connection to the sea, and strengthen and enhance the dominance of the inner-neighborhood open areas.

3.4.2. Three Actions

To achieve all these aims, three main actions must be taken, as follows:

1. Strengthening the old buildings and open spaces within the neighborhoods for the longtime residents. This includes adding varied uses and renovating the old buildings through the densification mechanism detailed in the introduction. This would maintain the existing community's resilience.
2. New construction of the edges of the existing neighborhoods along the five main avenues, adding uses currently lacking in Kiryat Yam. We propose diverse residential construction suitable for the middle–high and creative classes [20], who will drive the urban renewal and economy, coupled with workplaces, commercial areas and public services for all populations. Locating the new populations and uses at the edges of the avenues would direct the former to a distinctly urban space, thereby preventing their forced integration into old and unsuitable peripheral spaces. This action will contribute to the resilience of the entire city by boosting the economy, increasing physical and human diversity, and providing additional services to the entire population (see Figure 9).
3. Connecting the two networks. Continuous open areas need to be planned to connect the avenues and open public areas between the buildings of the old neighborhood, combined with the bicycle route network. Such connectivity will contribute to Kiryat Yam's open public spaces and to urban resilience overall through walkability, accessibility, and connectivity.

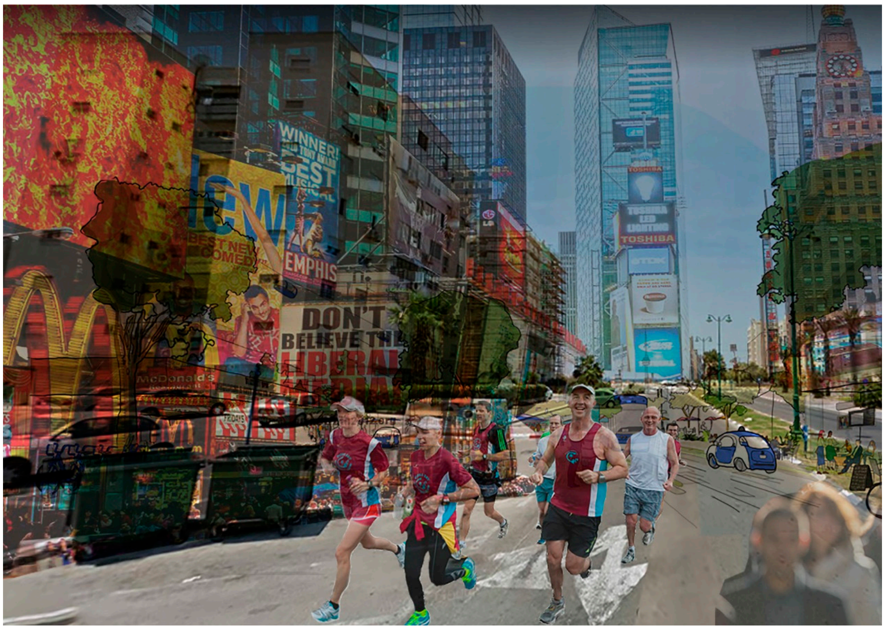


Figure 9. Conceptual simulation of the new urban space along the avenues. Athar Kabha, Tamar Eldar, and Idan Raz, WIZO Haifa Academic Center, 2018.

4. Discussion and Conclusions

Most studies on urban renewal do not address the physical aspects but rather focus on legal [44], economic [12], and social [43] dimensions. This article contributes to the limited research that explores the spatial dimension [45]. By analyzing conventional solutions, we propose an innovative spatial solution that is unique and innovative.

This article indicates that the solutions for urban renewal based on the infusion of new populations into aging or neglected neighborhoods are based on building new neighborhoods instead of those demolished. Since we are dealing with the geographical periphery, one of whose strengths is the community resilience already established in the old neighborhoods, we asked how this can be done without damaging the longtime residents' community resilience.

The logic behind our approach combines the needs of the city with the needs of the community. Given that the urban population is socioeconomically disadvantaged, the city has a significant interest in attracting a new population, serving as a kind of social and general rejuvenation for the city. On the other hand, in the old neighborhood, a cohesive community has formed that needs to be preserved. Moreover, the physical structure of the neighborhood, based on modernist low-rise buildings and diverse open spaces, provides numerous meeting places for the community. Hence, the proposed solution is derived; preserving the physical spaces of the old community, alongside new and extensive development for the benefit of a strong and new population that will propel the city forward.

The solution offered here may be captured in the term 'additional spatial network' (see Figure 10)—an additional network of housing and commercial, occupational, and other uses at the edges of the neighborhood. The new construction should face the five main roads dividing the city. Since these are two wide and too empty to begin with—the outcome of modernist planning that has prioritized transportation efficiency—this would also be an opportunity to narrow them and turn them from motorways into residential streets enabling pedestrian and bicycle traffic. When the city's walkability potential is high, and when the passage grid enables connectivity, this is a win–win solution: the old neighborhoods retain their community structure, and the new construction creates a new, street-oriented and vital urban system.

This solution offers multiple benefits. First, it outlines a way of solving the problems of urban renewal in the periphery [43]. Urban renewal in peripheral areas faces many obstacles, but more than that, it appears that the blocking point for promoting these processes is not clear. Our study suggests that longtime communities are attached to the place and are generally not interested in relocating, particularly because of their strong community and resilience. We argue that strengthening the local community, while enhancing the qualities of its living space that are appropriate for community living, will ensure the success of urban renewal in the periphery and contribute to overall urban resilience.

Second, new populations may contribute to the renewal of peripheral cities by developing new urban areas instead of vacant urban spaces, to create vital and functionally diverse streets. This way, both the creative and the middle–high classes will not feel forced to live in an old neighborhood characterized by neglected public housing blocks.

Third, by leaving old communities in their homes and surroundings, displacement and gentrification, which often occur in peripheral towns, can be prevented.

Fourth, leaving elderly populations in their place is essential for their sense of well-being, which is greatly affected by environmental changes.

Fifth, the remaining supply of low-cost apartments can also serve other demographic groups in various stages of their lifecycle, such as young couples, single and divorced people, and senior citizens.

Sixth, enhancing urban diversity in given areas by diversifying their inhabitants and the housing and public area patterns will contribute to the town's flexibility and, consequently, its community and urban resilience.

Finally, the proposed solution pays respect to the city's structural heritage, which is not destroyed to pave the way for the latest construction fashion (which is mostly more profitable for the entrepreneur).

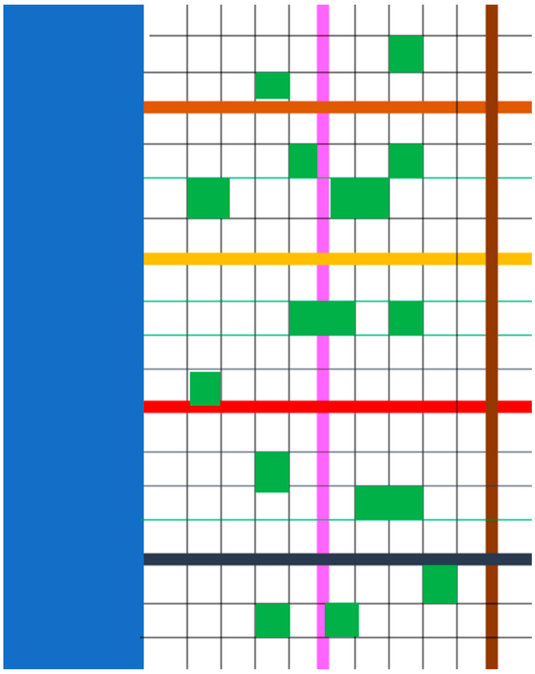


Figure 10. Planning concept scheme. An additional, constructed, and diverse-usage street network (thick and colored lines) replaces the roads that divide the city and connects to the inner-neighborhood grid and inner open spaces (the blue area represents the sea). The green areas represent urban parks in the city.

In conclusion, urban renewal in peripheral cities faces many human, structural, and economic obstacles. Relying on the resilience of the old population of the city and the spatial urban network that exists in it can promote urban renewal for the old population and integrate a new one. In any peripheral urban renewal, it is important to understand that urban networks vary from city to city, and the existing population as well as the existing urban network must be considered. Note, however, that this solution does not detract from the need to address specific issues related to the old construction, particularly in public spaces and all the more so in areas with weaker communities. The municipality is responsible for maintaining public areas, as well as for providing low-cost loans and professional assistance to those wishing to renovate their houses and adapt them to their needs.

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Article

The Impact of E-Commerce Transformation of Cities on Green Total Factor Productivity

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Abstract: The e-commerce-oriented transformation of cities is an important measure to enhance the vitality of economic development, improve the efficiency of resource allocation, and provide a new boost to the green and high-quality development of regions. Taking the quasi-natural experiment of national e-commerce demonstration city construction as the starting point, using the panel data of 281 prefecture-level cities in China from 2005 to 2021, we measure the green total factor productivity of cities by using the super-efficient SBM model with non-expected outputs and the global reference GML index method, and use the multi-period propensity score matching double-difference method to examine the impact of urban e-commerce-oriented transformation on the green total factor productivity of the city and the intrinsic mechanism of the effect. The results show that the urban e-commerce transformation policy can significantly promote regional green total factor productivity, and this result still holds after a series of robustness tests, such as changing the time point of the policy, randomly selecting the placebo proposal for the treatment group, and changing the matching method; the effect is regionally heterogeneous, and is more pronounced in large cities, non-provincial capitals, eastern cities, central cities, and non-resource-based cities; the urban e-commerce transformation mainly promotes the improvement of urban green total factor productivity through three channels: the industrial structure upgrading effect, the economic agglomeration effect, and the green technology innovation effect.

Keywords: e-commerce transformation of cities; green total factor productivity; e-commerce; industrial structure; economic agglomeration; green technological innovation

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1. Introduction

In response to climate change, many countries have increased their focus on carbon emissions and environmental protection issues by enacting stricter legislation and setting emissions targets (Fragkos et al., 2017) [1]. For example, the US passed the American Climate and Energy Security Act (ACESA) and proposed the Green New Deal, Japan formulated a master plan for a 'Green Development Strategy', and the EU released the '2020 Strategy', which has green growth as a core strategy to enhance the competitiveness of European countries.

China's economic growth and social development have made a qualitative leap in the context of forty years of reform and opening-up. However, against the backdrop of rising economic output, the situation of resource scarcity and environmental degradation has become increasingly serious. Relevant information shows that by 2022, China's comprehensive national power will rank 2nd in the world, while China's environmental quality will rank only 160th in the world in the Environmental Performance Index Report jointly published by Yale University and Columbia University. The concept of green development was first introduced into the country's five-year plan in the Outline of the Thirteenth Five-Year Plan for the National Economic and Social Development of the People's Republic of China (2016–2020), which states that green development is a sine qua non for sustainable development and that it is necessary to adhere to the basic state policy of conserving resources and protecting the environment. The addition of the word "beautiful" to the description of building a strong modern socialist country in the report of the 19th National Congress also highlights the importance of environmental issues. For the largest developing country, industrialization is still an important part of China's future economic growth, and how to avoid falling into the "middle-income trap" of low-end manufacturing accompanied by environmental pollution has become one of the key tasks of green development.

Under the global digitalization process, e-commerce has become an indispensable and important method for the economic development of cities. After the General Office of the State Council issued several opinions on accelerating the development of e-commerce in 2005, China's e-commerce industry responded quickly and played a positive role in improving the efficiency of resource allocation, promoting the development of small and medium-sized enterprises (SMEs), and boosting employment while enhancing the vitality of economic development. To further guide the e-commerce industry to develop steadily and play a more strategic role in economic development and social progress, the National Development and Reform Commission, the Ministry of Commerce, and other ministries and commissions have jointly carried out the establishment of "national e-commerce demonstration cities", with Shenzhen as China's first e-commerce demonstration city in 2009, and Beijing, Shanghai, Qingdao, and another 22 cities approved in 2011, 2014, and 2017, respectively, in accordance with the principle of "pilot first, step by step". In 2014 and 2017, a number of national e-commerce model cities were approved under the "pilot first, promote gradually" principle, and a total of 70 cities have been approved as national e-commerce model cities to date. These areas were approved for the construction of national e-commerce demonstration cities, i.e., urban e-commerce transformation cities that must give full play to the role of e-commerce in optimizing resource allocation, upgrading industrial structure, and promoting employment. Specifically, the aim is to vigorously develop e-commerce in agriculture, manufacturing, and traditional services, and vigorously develop e-commerce in the field of people's livelihood and cross-border e-commerce, so as to promote the transformation and upgrading of the economy; it is to establish a new mechanism adapted to the development of e-commerce, a new mode of e-commerce market governance, and a new regulatory framework that ensures that the healthy and rapid development of e-commerce is the top priority of city construction.

E-commerce not only implies a more convenient and efficient way of consumption, but also develops in a way that reduces energy consumption to a large extent (Abukhader, 2008) [2]. In particular, the Guiding Opinions on the Establishment of National E-commerce Demonstration Cities clearly states that the significance of establishing e-commerce demonstration cities is to "reduce the consumption of material resources and energy, reduce environmental pollution, develop a green economy, improve the industrial structure and optimise the allocation of resources". Its significance is highly consistent with the goal of green and high-quality development. Green total factor productivity, as an important indicator to measure the level of green and high-quality development of cities, has become a research topic of great interest to scholars at home and abroad.

Can an e-commerce-oriented progressive transformation (i.e., the construction of national e-commerce model cities) improve the green total factor productivity of cities? What are the main mechanisms by which it can do so? Answering the above questions is of great practical significance for China's transition to a green development model. In this context, this study adopts Chinese prefecture-level urban panel data, selects national e-commerce demonstration cities as quasi-natural experiments, and applies the multi-period PSM-DID methodology to study the promotion effect of urban e-commerce-based transformation on the improvement of green total factor productivity, so as to provide policy recommendations and empirical references for urban green development. The marginal contributions of this paper comprise four main aspects. First, this paper uses the data of 281 prefecture-level cities in China from 2005 to 2021 to validate the issue of the role of urban e-commerce-based transformation on the improvement of green total factor productivity, which broadens the idea of urban development research. Second, this paper verifies the issue by using the multi-period propensity matching score double-difference method to determine the net effect of urban e-commerce-based transformation on green total factor productivity enhancement, which overcomes the estimation bias in some previous studies, and uses various methods to test the robustness of the results. Third, this paper analyzes in detail the regional differences in green total factor productivity enhancement by urban e-commerce-oriented transformation in combination with cities of different levels, types, and locations. Fourth, this paper empirically tests the role path of urban e-commerce-oriented transformation on green total factor productivity improvement from the industrial structure upgrading effect, economic agglomeration effect, and green technology innovation effect, respectively, which enriches related research.

The rest of this paper is structured as follows: the first part describes the policy background of urban e-commerce transformation and puts forward the theoretical hypothesis of this paper; the second part mainly introduces the model construction, data source, and variable design of this paper; the third part is the empirical analysis of this paper, which presents the benchmark regression results, the parallel trend test and the counterfactual test, etc.; the fourth part is the test of the effect mechanism; the fifth part is the conclusions and policy recommendations.

2. Literature Review and Theoretical Background

2.1. Literature Review

At present, scholars are concerned about green total factor productivity and the construction of national e-commerce demonstration cities, and they have also conducted some studies and achieved results. In terms of the construction of national e-commerce demonstration cities, Shi (2022) [3], Jin et al. (2022) [4], Zhou et al. (2021) [5], Gao et al. (2021) [6], and Liu et al. (2021) [7] pointed out that the establishment of national e-commerce demonstration cities not only effectively improves the economic development of the region, but also plays an important role in promoting the green technological innovation of enterprises, the inflow of foreign direct investment, the promotion of industrial structural transformation, and the promotion of green high-quality development, all of which have significant positive impacts. In terms of green total factor productivity, Hu et al. (2011) [8], Wang et al. (2015) [9], and Yu et al. (2019) [10] incorporated the environmental pollution index into the non-parametric DEA–Malmquist index model beyond the logarithmic production function and the SBM model to calculate the green total factor productivity of China's provinces and cities and analyzed the trend of its development over time. Li et al. (2012) [11] analyzed the impact of environmental regulation on green total factor productivity in the manufacturing sector. Yuan et al. (2015) [12] and Chen (2018) [13] explored the influencing factors of China's industrial green total factor productivity and pointed out that China's industrial green total factor productivity is positively influenced by technological level and reasonable property rights structure, negatively influenced by capital deepening and unreasonable energy structure, and affected by foreign direct investment and environmental regulation. She et al. (2020) [14] conducted a study based on a quasi-natural experiment with the national low-carbon city pilot policy in 2010 and found that the policy can significantly improve urban green total factor productivity through technological innovation and industrial structure upgrading. Ge et al. (2018) [15], Shangguan et al. (2020) [16], and Huang et al. (2020) [17] pointed out that scientific and technological innovation, environmental regulation, and industrial agglomeration are important factors in improving green total factor productivity, respectively.

As opposed to the above research perspectives, this paper explores the causal relationship and influence mechanism between the construction of national e-commerce model cities and green development. Sui and Rejeski (2002) [18] and Tiwari and Singh (2011) [19] argue that the environmental impact of e-commerce is a double-edged sword. Zhang et al. (2022) [20] used data from 265 cities in China from 2007 to 2016 as a research sample and used a multi-period variation approach to test the impact of the national e-commerce model city pilot on urban environmental pollution. The results showed that after becoming a pilot city, urban environmental pollution was reduced by about 17.5% on average, which means that the national e-commerce model city policy significantly reduced urban environmental pollution. Di and Zhi-Ping (2023) [21] empirically investigated the impact and mechanism of the NEDC policy on urban CO_2 emissions using a multi-period difference-in-difference (DID) model and a mediated effects model and found that the national e-commerce demonstration city policy significantly reduced urban CO_2 emissions. Liu et al. (2023) [22] found that the national e-commerce model city construction policy achieved energy-saving effects through technological innovation, industrial reorganization, and economic agglomeration. The above literature review illustrates from various perspectives that the national e-commerce demonstration city policy, as a pilot policy, has generated the green economy effect of e-commerce while expanding the space for e-commerce development. However, there is no relevant scientific literature that explores whether and how the construction of national e-commerce model cities promotes the improvement of green total factor productivity in cities. Therefore, the relationship between e-commerce and green total factor productivity needs to be explored and verified with richer data and rigorous empirical methods.

2.2. Role Mechanism Analysis and Theoretical Hypothesis

Urban e-commerce transformation is an exploratory practice in China's reform process, and at the same time, it is the key to promoting green development. Based on previous studies, this paper argues that in the process of urban e-commerce transformation, i.e., the construction of national e-commerce demonstration cities, it mainly affects the green total factor productivity of cities through three aspects, namely the effect of upgrading the industrial structure, the effect of economic agglomeration, and the effect of improving the level of regional green technological innovation. The specific mechanism of the role is as follows.

First, the e-commerce-oriented transformation of cities has promoted green total factor productivity in cities by promoting the upgrading of industrial structure. From the technological perspective, the development of e-commerce has promoted the advancement of Internet technology, and enterprises have increased their technological investment, thereby improving their technological level and innovation capacity and promoting the upgrading of industrial structure. From the perspective of productivity, the application of e-commerce has led to the differentiation of productivity among different industries, and in the process of transferring production factors from low-productivity industries to high-productivity industries, the efficiency of social resource allocation has been improved, thus promoting the upgrading of industrial structure. From the perspective of consumer demand, the application of e-commerce enables producers and consumers to carry out low-cost, multi-channel communication, guiding consumer demand towards diversification and personalization, thus promoting the upgrading of industrial structure through changes in the structure of social demand and supply. From the perspective of employment demand, the development of e-commerce has brought a variety of jobs, such as customer service, operation, distribution, and so on, to the social service industry, expanding the proportion of the service industry in the national economy, while changing the original structure of the service industry and promoting the upgrading of the industrial structure. Obviously, the above industrial structure upgrading brought about by the transformation of e-commerce is detached from the high-energy-consuming and high-polluting industrial industry, reducing energy consumption and environmental pollution, and the industrial structure upgrading shows the green transformation mode of "service-oriented" industry (Shao et al., 2019) [23], which helps to improve the green total factor productivity of the city.

Second, the economic agglomeration caused by e-commerce transformation can promote green total factor productivity. Specifically, e-commerce transformation cities with favorable national policies and corresponding supporting policies from local governments have enabled the rapid development of related enterprises in the cities, promoted the rapid improvement of related infrastructure in the cities, such as integrated logistics warehousing and distribution systems and regional logistics and warehousing centers, attracted a large amount of capital and labor, and continuously increased the degree of economic agglomeration. This economic agglomeration can improve labor productivity and factor resource utilization efficiency while promoting technological innovation, and Glaeser (2012) [24] shows that the higher the degree of economic agglomeration, the higher the efficiency of energy and factor utilization, which in turn promotes the green total factor productivity of the city. Therefore, the higher the economic agglomeration brought about by the transformation of e-commerce, the more it contributes to the realization of green total factor productivity by promoting technological progress and production efficiency.

Finally, the urban e-commerce transformation promotes the green development of the economy by enhancing the green innovation capability of enterprises, thus improving the green total factor productivity. In the context of e-commerce-based transformation, traditional industries and e-commerce-based Internet enterprises integrate and penetrate each other, leading to the continuous updating and iteration of their original business models and production methods, which, on the one hand, optimizes the efficiency of resource allocation and, on the other hand, reduces energy consumption through technological iteration. Feng et al. (2016) [25] found that by exploring the new business model of B2B and B2C, this innovative business model makes the supply and demand relationship between enterprises and between enterprises and consumers personalized and efficient, which reduces the market-oriented transaction costs of enterprises. The reduction in transaction costs also plays a role in alleviating the financing constraints of enterprises and provides financial support for their green innovation. At the same time, the development and application of e-commerce has largely alleviated the market failure problems faced by enterprises in the process of green technology innovation, such as environmental externalities, path dependency and capital market imperfection, thus greatly reducing the variable costs in the production and sales process and providing more trial-and-error opportunities for enterprise innovation, which helps the R&D and shaping of green innovative technologies. Enterprises are gradually building a green, low-carbon, and recycling industrial system in the process of exploring green innovation, which enhances the green factors of production.

H1. *The e-commerce-oriented transformation of the city has a promoting effect on the green total factor productivity of the city.*

H2. *The e-commerce-oriented transformation of cities mainly promotes the improvement of green total factor productivity through the industrial structure upgrading effect, the economic agglomeration effect, and the effect of increasing the level of regional green technological innovation.*

3. Research Design

3.1. Model Setting

During the sample period, the sequential approval of e-commerce demonstration cities and the factor of whether they are approved or not leads to regional differences between each demonstration city and non-demonstration cities. To address this phenomenon, this paper adopts the DID method to control for such differences, which can on the one hand intuitively assess the policy effect of urban e-commerce transformation on green total factor productivity improvement, and on the other hand more effectively identify the net effect of urban e-commerce transformation on green total factor productivity. Since the approval of each national e-commerce demonstration city is not at the same time, there is a difference in the point in time at which each city is affected by the policy, so this paper relies on the method of Bertrand et al. (2004) [26], and takes the region that builds a national e-commerce demonstration city as the experimental group and the region that does not build a national e-commerce demonstration city as the control group, and sets up the following double-difference model to examine the impact of urban e-commerce transformation on green total factor productivity:

$$Gtfp_{i,t} = \beta_0 + \beta_1 Eco\_city_i \times Time_t + \gamma Controls_{i,t} + \delta_t + \mu_i + \varepsilon_{i,t} \quad (1)$$

where i denotes city and t denotes time. The explanatory variable Gtfp is green total factor productivity. Eco_city × time is a dummy variable for the year in which the national e-commerce pilot city policy was approved. It takes the value of 0 before being approved as a national e-commerce model city and takes the value of 1 after being approved as a national e-commerce model city (i.e., in that year and thereafter). Control is an ensemble of a number of control variables. δ_t is a time fixed effect that does not vary with individuals. μ_i is a region fixed effect that does not vary with time. ε_{it} is the model random error term. The regression coefficient β_1 measures the net policy effect of urban e-commerce transformation on regional green total factor productivity. If $\beta_1 > 0$, it means that urban e-commerce transformation is indeed conducive to increasing regional green total factor productivity, i.e., it proves hypothesis H1 put forward in this study. On the other hand, if $\beta_1 < 0$, it inhibits the increase in green total factor productivity, i.e., hypothesis H1 is not proved.

The double-difference method reduces the endogeneity problem caused by omitted variables in the regression equation to some extent, but the selection of the control group is more subjective and prone to the problem of sample selection bias. Since the government proposed the national e-commerce demonstration city construction project in 2009, regions have responded differently to the policy and implemented it to varying degrees. Although the policy of building national e-commerce model cities is a government act, it is not mandatory for regions, so there is likely to be a natural endogeneity between urban e-commerce transformation and green total factor productivity. Therefore, in order to further select an appropriate control group, this paper incorporates the propensity score matching (PSM) method, which is calculated as follows.

Based on the given covariates, the predicted probability of each city being approved to build a national e-commerce demonstration city, i.e., the propensity score P(Xi), is estimated by a logit model, which is calculated using the following formula:

$$P(X_i) = Pr(D_i = 1|X_i) = F[f(X_i)] \tag{2}$$

In Equation (2), X_i denotes the covariate of the ith city; D_i is the dummy variable of the city's e-commerce transformation, which takes the value of 1 for the approved construction of the national e-commerce demonstration city and 0 for the unapproved construction of the national e-commerce demonstration city; $f(X_i)$ is a linear function, and F[-] is a logit function. According to the propensity score, we use the relevant matching method to match the experimental group with the control group, find the unapproved construction of national e-commerce demonstration cities with similar propensity score values to the construction of national e-commerce demonstration cities as the control group, and perform DID estimation for the matched experimental group and control group using Equation (1) to obtain the average treatment effect of the policy.

The propensity score matching double-difference method (PSM-DID) effectively solves the problem of sample selection bias while overcoming the influence of unobservable and observable variables on sample selection, so that it can more accurately estimate the net effect of urban e-commerce transformation on the improvement of regional green total factor productivity.

3.2. Description of Variables

3.2.1. Explained Variables

This paper chooses green total factor productivity as an explanatory variable. In order to better reflect the strategic importance of green development, this paper simultaneously considers the efficiency requirements of the high-value development stage and environmental factors. Specifically, based on the methodology of Yu et al. (2021) [27], we use the super-efficiency SBM model based on the inclusion of non-desired outputs with the global reference GML index method to measure urban green total factor productivity. The relevant indicators and data processing of inputs, desired outputs, and non-desired outputs are described below:

(1) Input factors: input factors include labor input, capital input, and energy input. Among them, labor input is measured by the number of people employed in the city district, capital input is measured by the capital stock (measured by the perpetual inventory method based on Jun et al. (2004) [28]) and the built-up area of the city district, and energy input is measured by the value of global stabilized night light based on Wu et al. (2014) [29].
(2) Desired outputs: desired outputs are measured by the GDP of each city.
(3) Undesired outputs: undesired outputs are mainly measured by industrial wastewater emissions, sulfur dioxide emissions, and smoke and dust emissions.

3.2.2. Core Explanatory Variables

In this paper, the interaction term of the city grouping dummy variable and the policy time dummy variable, i.e., the city e-commerce transformation dummy variable (Eco_city × Time), is taken as the core explanatory variable.

3.2.3. Control Variables

According to the research of scholars, such as Li et al. (2018) [30] and Lin et al. (2019) [31], green total factor productivity is also affected by foreign direct investment (Fdi), the level of economic development of the city (Pgdp), the degree of government intervention (Gov), the level of foreign trade (Trade), and the level of urbanization and construction (Urban), so this paper takes the above variables as control variables.

3.3. Data Sources

This paper selects the panel data of 281 prefecture-level cities from 2005 to 2021 as the research sample. A total of 70 cities are e-commerce transformation cities, i.e., areas approved as national e-commerce demonstration cities during the study period, but based on the availability of data, this paper selects 68 of these e-commerce transformation cities as the experimental group of cities, and the rest as the control group of cities. The two cities with missing data are Yiwu City and Wujiaqu City. These two cities were not included in the model due to missing environmental data, such as industrial wastewater emissions, sulfur dioxide emissions and smoke and dust emissions, but this does not affect the empirical results. Among these, the list of cities approved as national e-commerce demonstration cities is obtained from the websites of the National Development and Reform Commission and the Ministry of Science and Technology, and from the websites of provincial governments (municipalities and autonomous regions). Other relevant data are obtained from the *China Urban Statistical Yearbook*, the *China Environmental Statistical Yearbook*, and the statistical yearbooks of provinces and cities over the years. Table 1 presents the definitions and descriptive statistics of the variables.

Table 1. Definition of variables and descriptive statistics.

Type of Variable	Definition of Variables	Variable Symbol	Mean	SD	Median
Explained variables	Green total factor productivity	Gtfp	0.998	0.054	0.997
Core explanatory variables	Dummy variable for urban e-commerce transformation policies	Eco_city × Time	0.110	0.313	0.000
Control variables	Foreign direct investment as a share of GDP	Fdi	0.019	0.020	0.012
	Natural logarithm of GDP per capita	Pgdp	10.380	0.767	10.424
	Local government fiscal expenditure as a share of GDP	Gov	0.177	0.096	0.154
	Import and export as a share of GDP	Trade	0.168	0.328	0.064
	Urbanization rate	Urban	3.920	0.311	3.926

4. Empirical Results and Analysis

4.1. Propensity Score Matching Process and Parallel Trend Test

In order to select suitable reference objects for e-commerce transformation cities, this paper is based on the logit regression model, using the one-to-one nearest neighbor propensity score matching method within the caliper range to match, and imposing the "common support" condition. The results are presented in Figure 1 and Table 2. As shown in Figure 2, after kernel matching, the kernel density curves of the treatment group and the control group basically coincide, indicating that the matching effect is better.

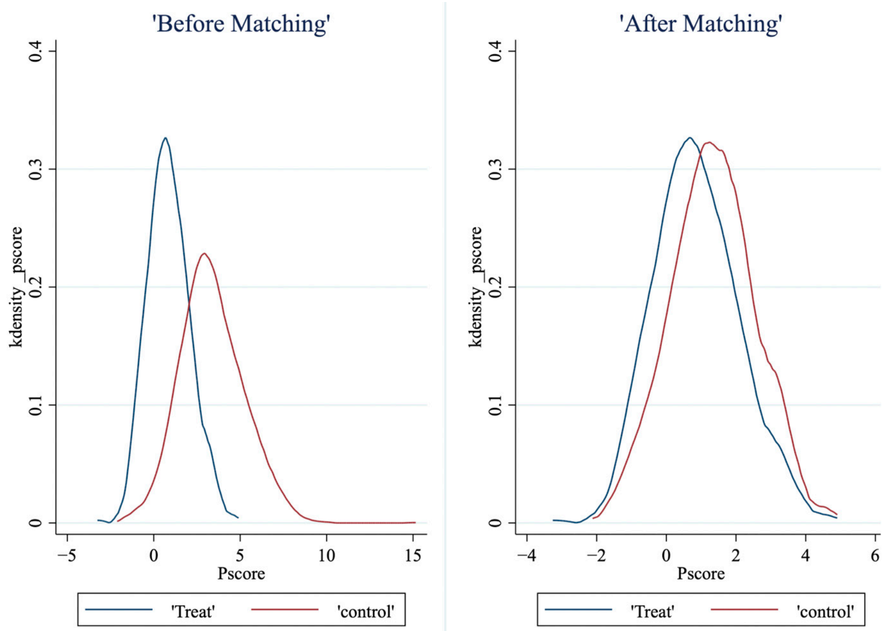

Figure 1. Kernel density distribution before and after PSM.

Table 2. Results of the propensity score matching balance test.

Variable	Sample	Mean Difference Test Treatment Group Mean	Control Group Mean	t-Value (*p*-Value)	Standardized Deviation Test Standardized Deviation	Deviation Drop in Deviation (%)
Fdi	Before matching	0.02456	0.0178	7.02 (0.000)	33	
	After matching	0.02457	0.02406	0.37 (0.710)	2.5	92.4
Pgdp	Before matching	11.248	10.273	29.12 (0.000)	160.2	
	After matching	11.245	11.243	0.06 (0.953)	0.3	99.8
Gov	Before matching	0.15519	0.1799	−5.40 (0.000)	−29.1	
	After matching	0.15526	0.15012	1.14 (0.255)	6	79.2
Trade	Before matching	0.3091	0.15085	10.24 (0.000)	45.8	
	After matching	0.30582	0.30026	0.23 (0.822)	1.6	96.5
Urban	Before matching	4.2344	3.881	25.52 (0.000)	140.9	
	After matching	4.2337	4.2414	−0.63 (0.532)	−3.1	97.8

Table 2 shows the matching effect of one-to-one near-neighbor propensity scores within the caliper range before and after the implementation of the urban e-commerce transformation policy, and the results of the balance test. As can be seen from the results, after the treatment by PSM, the difference between the treatment group and the control group is significantly reduced, the standard deviations of the control variables have all decreased, the absolute values are all less than 10%, the P values of the balance test of the control variables after the matching are all greater than 10%, the original hypothesis cannot be rejected, there is no significant difference between the experimental group and the control group in the matching variables after the matching, and the whole sample meets the requirements of the balance test. Therefore, the choice of matching method in this paper is reasonable, the variables are valid after matching, and the matching results better balance the data. The matched data can lay the foundation for further multi-period DID estimation, and the following empirical studies are estimated and analyzed with the matched samples.

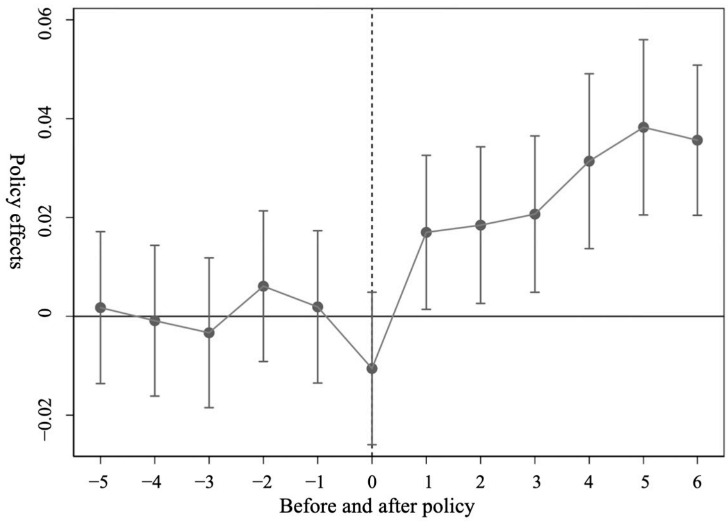

Figure 2. Parallel trend test.

In the sample interval, the status of a city as a treatment or control group changes according to the year in which the national e-commerce demonstration city is approved, and if the policy is not implemented in a city, the green total factor productivity of the control group and the experimental group should maintain a parallel trend of change. Therefore, in this paper, before using the double-difference method for policy evaluation, the dynamic test of the policy implementation effect was carried out by the event analysis method by cross-multiplying the time dummy variable before the policy implementation with the dummy variable of the national e-commerce demonstration city policy, so as to test the parallel trend hypothesis. The construction model is shown in the following Equation (3):

$$Y_{i,t} = \alpha + \sum_{k=-12}^{k=11} \beta_k \times Year_{i,k} + \gamma Controls_{i,t} + \delta_t + \mu_i + \varepsilon_{i,t} \quad (3)$$

where a series of dummy variables $\mathrm{Year}_{\mathrm{i,k}}$ denotes the kth year when the pilot policy of urban e-commerce transformation started to be implemented in city i. β_k denotes the difference between the treatment group and the control group after the kth year of policy implementation, which is the core parameter of the equation. When $k < 0$, if none of the estimates of β_k are significant, it means that the treatment and control groups satisfy the ex ante parallel assumption, in which case the results of the double-difference method are reliable; on the contrary, if at least one of the estimates of β_k is significant during the period $k < 0$, it means that the parallel trend assumption is not satisfied. The parallel trend dynamics of green total factor productivity as an explanatory variable are shown in Figure 2.

As can be seen from Figure 2, the estimated values of green total factor productivity as an explanatory variable do not pass the significance level test in the period of $k < 0$. It can be seen that there is no significant difference in the level of green total factor productivity between the experimental group of cities and the control group of cities before the approval of the construction of the national e-commerce demonstration city, and the estimated coefficient of the policy dummy variable hovers around zero, which meets the requirements of the parallel trend assumption. Further analysis of Figure 2 shows that in the year of policy implementation, the explanatory variables still fail the 5% confidence level test, indicating that there is a 1-year lag in the impact of urban e-commerce transformation on the total green factor. In addition, during $k > 0$, the dynamic intensity of the impact of urban e-commerce transformation on total green factors is proportional to time, indicating that the marginal contribution of the impact of urban e-commerce transformation on total green factors continues to increase.

4.2. Benchmark Model Regression

Under the premise of satisfying the parallel trend assumption, this paper uses the data after PSM to test the relationship between urban e-commerce transformation and urban green total factor productivity using a two-way fixed-effects multi-period DID model controlling for area and time effects. Taking model (1) as the basis of analysis and gradually adding control variables for regression analysis, the results of the estimation are shown in Table 3. The results of columns (1)–(6) in Table 3 show that the estimated coefficients of Eco_city × Time are significantly positive at the 1% significance level, both when controlling only for area fixed effects and time fixed effects without adding the control variables, and after gradually adding the control variables that affect green total factor productivity. In addition, the results of column (6) indicate that, all other things being equal, the green total factor productivity level of a city increases by about 1.4% on average after it is approved as a national e-commerce demonstration city, which means that the transformation of urban e-commerce can help promote the improvement of green total factor productivity, and this result provisionally confirms the research hypothesis H1 proposed in this paper.

Table 3. Test results of the impact of the construction of national e-commerce model cities on green total factor productivity.

	(1)	(2)	(3)	(4)	(5)	(6)
Eco_city × Time	0.017 ***	0.016 ***	0.016 ***	0.015 ***	0.014 ***	0.014 ***
	(3.95)	(3.71)	(3.72)	(3.39)	(3.29)	(3.31)
Fdi		−0.375 ***	−0.369 ***	−0.352 ***	−0.343 ***	−0.343 ***
		(−4.96)	(−4.85)	(−4.60)	(−4.49)	(−4.48)
Pgdp			−0.004	−0.010	−0.009	−0.009
			(−0.59)	(−1.50)	(−1.28)	(−1.33)
Gov				−0.061 **	−0.058 **	−0.058 **
				(−2.42)	(−2.30)	(−2.30)
Trade					−0.009 **	−0.010 **
					(−2.39)	(−2.41)
Urban						0.005
						(0.38)
_cons	0.956 ***	0.969 ***	1.004 ***	1.073 ***	1.061 ***	1.045 ***
	(139.09)	(131.79)	(16.85)	(16.28)	(16.07)	(13.25)
Year	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
N	3736	3736	3736	3736	3736	3736
R2	0.108	0.114	0.114	0.116	0.117	0.117

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

4.3. Robustness Tests

4.3.1. Placebo Test: Changing the Time of the Intervention

In order to ensure the validity of the policy treatment effects, this section uses a placebo test to rule out spurious regressions due to omitted variables and, thus, ensure the reliability of the benchmark results. In this section, four spurious model city policy variables (Eco_cityplacebo4, Eco_cityplacebo5, Eco_cityplacebo6 and Eco_cityplacebo7) are created by varying the timing of the policy, i.e., creating a spurious policy timing by advancing the policy by 4–7 years. They are then analyzed using the benchmark model (1). If the coefficient of Eco_cityplacebo is no longer significant under this result, it means that the parallel trend hypothesis is still valid and the policy of "establishing a national e-commerce demonstration city" can have a positive impact on the city's green total factor productivity. On the other hand, it means that the parallel trend hypothesis is not satisfied and the increase in the green total factor productivity of the cities in the treatment group is related to other stochastic factors rather than being influenced by the policy.

The results of the time placebo test are shown in Table 4: the estimated coefficients are insignificant when the policy is assumed to have been implemented 4, 5, 6, and 7 years earlier, i.e., the parallel trend hypothesis still holds and the policy of establishing a "National E-commerce Demonstration City" influences the increase in green TFP of the treatment group cities rather than this being caused by random factors. This counterfactual test confirms the robustness of the above estimates.

Table 4. Counterfactual test for the point at which the change in policy occurs.

	(1)	(2)	(3)	(4)
Eco_cityplacebo4	0.005			
	(1.03)			
Eco_cityplacebo5		0.002		
		(0.37)		
Eco_cityplacebo6			−0.001	
			(−0.24)	
Eco_cityplacebo7				−0.007
				(−0.95)
Fdi	−0.347 ***	−0.350 ***	−0.354 ***	−0.358 ***
	(−4.52)	(−4.56)	(−4.61)	(−4.66)
Pgdp	−0.009	−0.010	−0.010	−0.010
	(−1.38)	(−1.40)	(−1.41)	(−1.41)
Gov	−0.066 ***	−0.067 ***	−0.069 ***	−0.069 ***
	(−2.61)	(−2.68)	(−2.73)	(−2.77)
Trade	−0.010 **	−0.010 **	−0.010 **	−0.010 **
	(−2.52)	(−2.53)	(−2.52)	(−2.49)
Urban	0.003	0.003	0.003	0.004
	(0.22)	(0.22)	(0.23)	(0.25)
_cons	−0.347 ***	−0.350 ***	−0.354 ***	−0.358 ***
	(−4.52)	(−4.56)	(−4.61)	(−4.66)
Year	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes
N	3736	3736	3736	3736
R2	0.115	0.115	0.114	0.114

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

4.3.2. Placebo Test: Randomly Selected Treatment Group

Although some city characteristic variables have been controlled in the quasi-natural experiment, there may still be some unobserved city characteristic factors that may affect the evaluation results of the pilot policies of e-commerce-oriented transition cities. As shown by Liu et al. (2015) [32], for the simultaneous point DID model, it is sufficient to randomly select a number of cities equal to the number of actual pilot cities from all sample cities as the treatment group. For the multi-temporal DID model with different policy shock times, it is necessary to randomly select a sample period for each sample object as the policy time, that is, to randomly generate the pseudo-group dummy variable $Group^{random}$ and the pseudo-policy shock dummy variable $Post^{random}$ at the same time.

Based on this, this paper constructs 500 random shocks of the pseudo-e-commerce transformation city pilot policy on 281 sample cities; each time, 68 of them are randomly selected as the experimental group, and the policy implementation time is also randomly given to obtain the 500 group dummy variables $Eco\_city \times Time^{random}$ (i.e., $Group^{random} \times Post^{random}$) to perform the placebo test to ensure the robustness of the estimation results. The kernel densities of the 500 estimated coefficients and their *p*-value distributions are shown in Figure 3.

The results show that the estimated coefficients generated during the randomization process are mainly concentrated around the value of 0, and the *p*-values are mostly higher than 0.1, while the estimated coefficient of the baseline regression of the actual policy is 0.017, which is significantly different from the results of the placebo test. The results are robust.

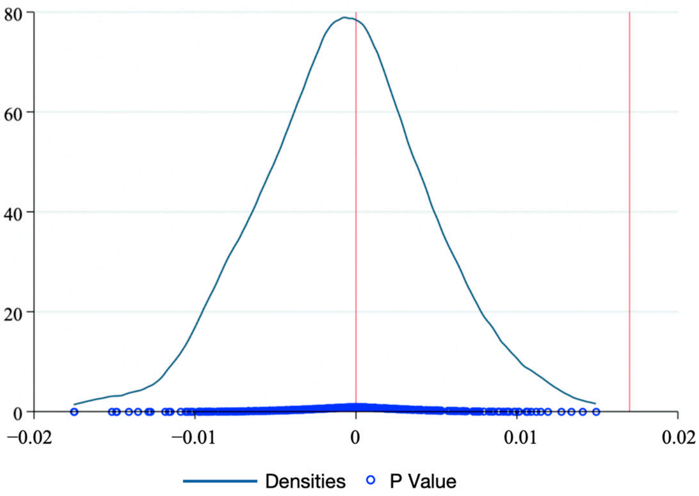

Figure 3. Distribution of coefficient estimates after stochastic treatment.

4.3.3. Transform Matching Method

Before double-differencing, this paper uses the one-to-one nearest neighbor propensity score matching method within the caliper range to match the experimental group with a similar control group. To test the robustness of the results, this paper transforms the matching method by using the kernel matching method and the radius matching method to match the experimental group with a similar control group based on the original data, respectively, and then double-differencing is performed after matching the control group. The coefficients in columns (1)–(4) of Table 5 are all significantly positive at the 1% significance level, which is consistent with the previous estimation conclusion that the matching method is robust and that the empirical results are reliable.

Table 5. Robustness test of transformed matching methods.

	(1) **Radius Matching**	(2) **Radius Matching**	(3) **Kernel Matching**	(4) **Kernel Matching**
Eco_city × Time	0.034 *** (8.39)	0.014 *** (3.05)	0.037 *** (10.28)	0.014 *** (3.53)
Fdi		−0.151 * (−1.69)		−0.198 *** (−2.69)
Pgdp		0.006 (0.69)		0.001 (0.16)
Gov		−0.035 (−1.33)		−0.048 * (−1.94)
Trade		−0.013 * (−1.91)		−0.023 *** (−3.82)
Urban		0.007 (0.33)		0.016 (0.94)
_cons	0.999 *** (715.50)	0.889 *** (8.14)	0.998 *** (907.26)	0.897 *** (10.38)
Year	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes
R^2	0.038	0.190	0.036	0.157

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

4.4. Heterogeneity Analysis

4.4.1. Heterogeneity of City Size

This paper first conducts a heterogeneity analysis of the impact of urban e-commerce transformation on urban green total factor productivity based on differences in city size, and divides the sample cities into two sub-samples of large cities and small and medium-sized cities based on the criteria proposed by the *Green Book on Small and Medium-Sized*

Cities (small cities with less than 500,000 urban residents, medium-sized cities with half a million to 1 million residents, and large cities with a population of 1 million or more), and conducts a group regression accordingly. The results are reported in Table 6, where column (1) shows the regression results for large cities and column (2) shows the regression results for small and medium-sized cities.

Table 6. Heterogeneity analysis of large and small and medium-sized cities.

	(1) Large Cities	(2) Small and Medium Cities
Eco_city × Time	0.016 **	0.013
	(2.25)	(1.64)
Fdi	−0.579 ***	−0.122
	(−4.13)	(−1.61)
Pgdp	0.010	0.012 ***
	(1.11)	(3.86)
Gov	−0.009	0.040 **
	(−0.20)	(2.23)
Trade	−0.020 **	−0.004
	(−2.10)	(−1.13)
Urban	0.078 **	0.004
	(2.45)	(0.39)
_cons	0.599 ***	0.847 ***
	(5.68)	(25.06)
Year	Yes	Yes
City	Yes	Yes
N	1529	2207
R^2	0.073	0.027

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

The results show that the contribution of urban e-commerce transformation to green total factor productivity is more significant in large cities. This may be due to the fact that large cities have more high-quality labor, high-quality innovation factors, and better capital environments than small and medium-sized cities. These cities can promote the innovation and upgrading of energy-saving and emission-reducing technologies through mechanisms, such as the sharing effect and the learning effect, and, thus, have more efficient energy use and stronger pollutant treatment capacity. As a result, pollutant emissions are greatly reduced, which in turn promotes the improvement of urban green total factor productivity. Based on the above analysis, the promoting effect of urban e-commerce transformation on urban green total factor productivity is mainly reflected in large cities.

4.4.2. Heterogeneity of Cities in the East, Central and West

This section examines whether the impact of urban e-commerce transformation on urban green total factor productivity shows heterogeneity among cities in the three economic zones of East, Central, and West, as divided by the National Bureau of Statistics of China. The regression results of the subgroups of the three sub-sample cities in the East, Central, and West regions are shown in Table 7.

Looking at columns (1)–(3), it can be seen that the impact of urban e-commerce transformation on regional green total factor productivity is significantly different in the three major economic zones. Among them, the eastern and central regions are more sensitive to the establishment of national e-commerce demonstration cities, and the green total factor productivity is significantly improved, while the western region has no significant improvement effect. Combined with the reality analysis of the three economic zones, the level of economic development in the western region is relatively low, although in recent years the western region has experienced "western development" and other policies to accelerate its economic development. However, compared with the eastern and central regions there is still a short period of time in which it is difficult to close the gap, which is the core of the regression results of the core factors of the difference. For the central and eastern regions with a higher level of economic development, the material foundation and capital environment for the development of e-commerce existed before the implementation of the policy, so it is easier for them to form a more complete "e-commerce" network through the integration of resources and production factors under the driving force of the policy. In addition, with the upgrading of the industrial structure, the three high-polluting, high-energy-consuming, and high-emission enterprises in these regions will be gradually reduced, thereby promoting the economy through industry and improving the green total factor productivity of the region.

Table 7. Heterogeneity analysis of eastern, central, and western cities.

	(1) Eastern Cities	(2) Central Cities	(3) Western Cities
Eco_city × Time	0.015 *	0.023 ***	0.002
	(1.82)	(3.63)	(0.28)
Fdi	−0.399 ***	−0.247 **	−0.038
	(−2.86)	(−2.51)	(−0.18)
Pgdp	0.000	−0.027 ***	0.024 ***
	(0.02)	(−2.79)	(4.65)
Gov	−0.090 *	−0.061 *	0.035
	(−1.82)	(−1.68)	(1.07)
Trade	−0.011 *	0.003	−0.009
	(−1.89)	(0.23)	(−1.37)
Urban	−0.012	0.044 ***	−0.015
	(−0.30)	(2.81)	(−0.94)
_cons	1.034 ***	1.061 ***	0.798 ***
	(5.48)	(10.29)	(14.26)
Year	Yes	Yes	Yes
City	Yes	Yes	Yes
N	1491	1288	957
R^2	0.114	0.199	0.047

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

4.4.3. Heterogeneity of Urban Resource Endowment

In order to investigate whether the impact of urban e-commerce transformation on urban green total factor productivity shows heterogeneity under different urban resource endowment conditions, the division criteria for resource-oriented cities used in this section refers to the National Sustainable Development Plan for Resource-Based Cities (2013–2021) issued by the State Council, the 126 prefecture-level cities in the sample cities are classified as resource-oriented cities, and the remaining prefecture-level cities are classified as non-resource-oriented cities. The same grouped regressions are run for the sub-sample of resource-oriented cities and the sub-sample of non-resource-oriented cities, and the results are reported in Table 8.

The results show that the transformation of urban e-commerce has a positive impact on the green and high-quality development of both resource-based and non-resource-based cities, and that it is more significant in non-resource-based cities. The reason is that the economic development of resource-based cities has long depended on local natural resources, such as coal, oil, and natural gas, and, therefore, there are more heavy industrial bases with "high energy consumption, pollution and emissions". For the establishment of e-commerce cities, the problems of backward infrastructure, technological capacity and irrational industrial layout will be more prominent, and the implementation of green and high-quality development will face greater difficulties, so the transformation of urban e-commerce may not have a significant impact on the green total factor productivity of the city in the short term. However, from a long-term perspective, such cities have great development potential, and with the landing and penetration of Internet technology and high-tech enterprises, the driving effect of urban e-commerce transformation for resource cities will be more extensive and profound.

Table 8. Heterogeneity analysis of resource-based and non-resource-based cities.

	(1) Resource-Based Cities	(2) Non-Resource-Based Cities
Eco_city × Time	0.012	0.012 **
	(1.44)	(2.47)
Fdi	−0.146	−0.145 *
	(−1.15)	(−1.66)
Pgdp	0.012	0.002
	(1.33)	(0.25)
Gov	0.015	−0.076 **
	(0.43)	(−2.42)
Trade	−0.002	−0.010 **
	(−0.15)	(−2.05)
Urban	0.017	−0.022
	(0.91)	(−0.88)
_cons	0.813 ***	1.026 ***
	(8.30)	(8.69)
Year	Yes	Yes
City	Yes	Yes
N	1466	2270
R^2	0.145	0.117

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

5. Testing the Mechanism of Action

Based on the research results in Section 3, this section further studies the impact mechanism of urban e-commerce transformation on green total factor productivity. From the logic of mechanism analysis, it can be seen that urban e-commerce transformation mainly affects urban green total factor productivity through three channels: the industrial structure upgrading effect, the economic agglomeration effect, and the green technology innovation effect, and this section further analyses in depth whether urban e-commerce transformation affects green total factor productivity through the above three mechanisms. In this regard, this paper adopts the approach of Quan et al. (2022) [33] to test the mechanism of action using two steps: (1) Testing the impact of urban e-commerce-based transformation on industrial structure upgrading, economic agglomeration, and green technological innovation; if urban e-commerce-based transformation improves industrial structure upgrading, economic agglomeration. and green technological innovation, it will tentatively support the logic of the above mechanism analysis; (2) by using the median of regional industrial structure upgrading level, economic agglomeration level, and green technological innovation level for a group test to further clarify how urban e-commerce-oriented transformation affects green total factor productivity.

5.1. Mechanism Test of Industrial Structure Upgrading Effect

The transformation of urban e-commerce plays an important role in promoting the application and development of e-commerce, and the factors of labor, capital, and technology will be concentrated in the more efficient information technology and service sectors, which will optimize the industrial structure of the city, and then accelerate the process of "retreating into three" of the city through the upgrading of industrial structure. This green transformation of the "service-oriented" city can help reduce energy consumption and environmental pollution and can improve the total factor productivity of the urban green sector. In this section, the ratio of the output value of tertiary industry to that of secondary industry (IS_TS) is used to measure the dynamic transformation mode of "retreating from the second and advancing to the third", the index of industrial structure upgrading is used to measure the transformation and upgrading of industrial structure (IS_upgrade), and the test results of the effect of industrial structure upgrading are shown in Table 9.

Table 9. Mechanism test of industrial structure upgrading effect.

	(1) IS_TS	(2) IS_TS < p50	(3) IS_TS > p50	(4) IS_Upgrade	(5) IS_Upgrade < p50	(6) IS_Upgrade > p50
Eco_city × Time	0.071 ***	0.057 *	−0.014	0.025 ***	0.038 ***	−0.004
	(4.39)	(1.68)	(−1.50)	(6.37)	(10.07)	(−0.45)
Fdi	−1.089 ***	−1.378 ***	−0.262 *	−0.223 ***	−0.371 ***	−0.048
	(−3.78)	(−2.66)	(−1.66)	(−3.27)	(−5.44)	(−0.43)
Pgdp	−0.341 ***	−0.308 ***	−0.280 ***	0.061 ***	0.032 ***	0.047 ***
	(−12.46)	(−5.03)	(−18.96)	(17.70)	(7.73)	(10.35)
Gov	1.071 ***	1.631 ***	0.101	0.192 ***	0.385 ***	0.033
	(10.86)	(7.01)	(1.29)	(9.96)	(10.22)	(1.61)
Trade	−0.007	−0.003	−0.017	−0.003	−0.008 ***	−0.002
	(−0.40)	(−0.12)	(−1.56)	(−0.85)	(−2.62)	(−0.32)
Urban	0.062	0.090	0.302 ***	0.246 ***	0.169 ***	0.184 ***
	(0.96)	(0.74)	(8.68)	(21.49)	(11.12)	(12.79)
_cons	3.664 ***	3.239 ***	2.078 ***	0.622 ***	1.303 ***	0.975 ***
	(11.44)	(4.76)	(12.26)	(16.18)	(22.00)	(20.10)
Year	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
N	3736	1868	1868	3736	1868	1868
R^2	0.635	0.566	0.636	0.505	0.541	0.309

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

From the regression results in columns (1) and (4), it can be seen that the implementation of urban e-commerce transformation (Eco_city × Time) significantly improves the regional industrial structure upgrade, which confirms the inference of this paper. Furthermore, this paper divides the samples into the advanced industrial structure group and the primary industrial structure group by the median of IS_TS and IS_upgrade to test the mechanism of urban e-commerce transformation on regional green total factor productivity in different contexts, and the test results are shown in columns (2)–(3) and (5)–(6), respectively. As can be seen from the results, in the primary group of industrial structure, the coefficient of urban e-commerce-oriented transformation is positive and significant at the 1% level. Meanwhile, in the advanced group of industrial structure, the urban e-commerce transformation is not significant. Overall, the test results of the above two-step method indicate that the implementation of urban e-commerce-oriented transformation improves the regional green total factor productivity by improving the regional industrial structure upgrading, i.e., it confirms the establishment of the industrial structure upgrading effect.

5.2. Mechanism Test of Economic Agglomeration Effect

To test the mechanism of the economic agglomeration effect, this paper uses the ratio of total non-agricultural output (i.e., the sum of the value added of secondary and tertiary industries) to the sum of the administrative area of these cities to measure economic agglomeration (ag). The results of the test of the economic agglomeration effect are shown in Table 10.

Table 10 columns (1) to (3) are the test results of economic agglomeration effect, from the regression results in column (1), it can be seen that the implementation of urban e-commerce transformation (Eco_city × Time) significantly improves the regional economic agglomeration, which preliminarily supports the inference of this paper. Furthermore, this paper takes the median regional economic agglomeration as the grouping criterion, divides the sample into higher economic agglomeration group and lower economic agglomeration group, and tests the mechanism of the city's e-commercialization transformation affecting the regional green total factor productivity in the case of higher economic agglomeration group and lower economic agglomeration group, respectively, and the results of the mechanism test are shown in columns (2) and (3), respectively. As can be seen from the results, the Eco_city × Time coefficient is positive and significant at the 1% level in the lower economic agglomeration group sample. On the other hand, Eco_city × Time is not significant in the higher economic agglomeration group. Therefore, the above test of the two-step method shows that the implementation of urban e-commerce transformation increases the level of regional green total factor productivity by increasing regional economic agglomeration, i.e., it confirms that the economic agglomeration effect holds.

Table 10. Mechanism test of economic agglomeration effect and green technology innovation effect.

	(1) Ag	(2) ag < p50	(3) ag > p50	(4) Tech	(5) Tech < p50	(6) Tech > p50
Eco_city × Time	0.226 ***	0.190 ***	0.003	0.023 ***	0.032 ***	−0.010
	(9.96)	(4.86)	(0.75)	(6.11)	(8.52)	(−1.17)
Fdi	−1.188 ***	0.337	−0.047	−0.245 ***	−0.352 ***	−0.069
	(−3.00)	(0.50)	(−0.86)	(−3.64)	(−4.98)	(−0.66)
Pgdp	−0.052	0.031	0.034 ***	0.037 ***	0.029 ***	0.013 ***
	(−1.48)	(0.41)	(8.32)	(10.12)	(6.65)	(2.75)
Gov	−0.833 ***	−1.910 ***	−0.069 ***	0.252 ***	0.486 ***	0.075 ***
	(−6.37)	(−3.26)	(−4.55)	(12.70)	(11.85)	(3.67)
Trade	−0.396 ***	−0.464 ***	−0.001	−0.006	−0.008 **	−0.004
	(−19.24)	(−14.35)	(−0.38)	(−1.56)	(−2.24)	(−0.55)
Urban	−0.495 ***	−1.516 ***	0.071 ***	0.357 ***	0.176 ***	0.347 ***
	(−6.71)	(−8.35)	(8.27)	(26.30)	(9.90)	(19.33)
_cons	2.576 ***	5.921 ***	−0.412 ***	0.424 ***	1.291 ***	0.685 ***
	(6.31)	(6.47)	(−8.93)	(10.11)	(19.62)	(12.95)
Year	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
N	3736	1868	1868	3455	1728	1727
R^2	0.317	0.422	0.133	0.534	0.540	0.383

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

5.3. Mechanism Test of Green Technology Innovation Effect

To test the mechanism of the green technology innovation effect, this paper selects the number of green patent applications per capita in each city from 2005 to 2021 to measure the level of green technology innovation in the region, and the test results of the green technology innovation effect are shown in Table 10.

Table 10 columns (4)–(6) show the mechanism of green technology innovation effect test results, and column (4)'s regression results show that the implementation of urban e-commerce transformation (Eco_city × Time) significantly improves the level of regional green technological innovation, preliminary confirmation of this paper's inference. Next, this paper takes the median level of regional green technological innovation as the grouping benchmark, divides the sample into a higher level of green technological innovation and lower level of green technological innovation group, respectively, and tests the impact mechanism of urban e-commerce transformation on regional green total factor productivity in the context of the higher level of green technological innovation and lower level of green technological innovation group; the empirical results are shown in columns (5) and (6), respectively. As can be seen from the results, in the sample of the lower level of green technological innovation group, the Eco_city × Time coefficient is positive and significant at the 1% level. On the other hand, Eco_city × Time is not significant in the higher level green technology innovation group. Through the above two-step test, it can be seen that the implementation of urban e-commerce transformation increases the level of regional green total factor productivity by increasing the level of regional green technological innovation, which confirms that the green technological innovation effect is established.

6. Conclusions and Discussion

This paper uses prefecture-level urban panel data from 2005 to 2021 to study the impact of urban e-commerce-oriented transformation policies on green total factor productivity in pilot regions using the multi-period PSM-DID model, based on which the impact mechanisms are tested, respectively. The results showed that: (1) urban e-commerce-oriented transformation policies can significantly promote regional green total factor productivity; in order to test the reliability of the benchmark regression results, this paper further conducts a robustness test on the benchmark regression results by changing the time point of the policy occurrence for the counterfactual test, the placebo test, and transforming the matching method, etc., and the results prove the validity as well as the reliability of the benchmark regression results. (2) There is regional heterogeneity in the effect of urban e-commerce transformation policy, and the effect of urban e-commerce transformation policy on the improvement of urban green total factor productivity is greater in large cities, eastern cities, central cities, and non-resource cities than in small and medium-sized cities, western cities, and resource cities. (3) Urban e-commerce transformation mainly affects urban green total factor productivity through three channels: the industrial structure upgrading effect, the economic agglomeration effect, and the green technology innovation effect. The above findings support the hypotheses H1 and H2 proposed in this paper. Meanwhile, the conclusions of this paper are similar to the findings of Zhang et al. (2022) [20], Di and Zhi-Ping (2023) [21], Liu et al. (2023) [22], etc., which confirm that the policy of building e-commerce demonstration cities can reduce urban environmental pollution.

The research in this paper is of great importance for developing countries and globally. On the one hand, it provides empirical evidence for the construction of national e-commerce model cities. On the other hand, it also provides a reference for the promotion of e-commerce model cities in developing countries. The empirical evidence in this paper shows that such policies are effective even in developing countries. Therefore, governments can further extend these experiences to more countries and regions and use policies conducive to the development of e-commerce to effectively promote green development. Based on the above conclusions, this paper makes the following policy recommendations from the macro and industry perspectives. From the macro perspective, it is necessary to make full use of the policy implementation effect of the national e-commerce demonstration city to further play its strategic role in reducing environmental pollution and improving the efficiency of resource allocation. At the same time, it is necessary to focus on relevant infrastructure construction and investment in small and medium-sized cities and western regions to further narrow the technology gap and improve innovation capacity. In addition, the transformation of e-commerce is both an opportunity and a challenge for resource-oriented cities, which should actively plan and carry out the construction of e-commerce demonstration cities with urban characteristics and advantages according to local conditions and eliminate blind promotion. At the industrial level, in conjunction with the center of gravity of China's economic development, we should accelerate the development of intelligent manufacturing industry with e-commerce as the link, cultivate new industries and new kinetic energy by improving the innovation capacity of green technology, build green and low-carbon industrial clusters, and further promote green and high-quality developments.

Although this paper discusses the e-commerce transformation of cities to promote green total factor productivity, the research object of this paper is only the "national e-commerce demonstration city" policy implemented in China, and it does not compare with the policies of other countries around the world, which can be considered for comparative analysis in the future.

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sustainability

Article

Sustainability of Urban Parks: Applicable Methodological Framework for a Simple Assessment

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Abstract: Urban parks are central to advancing urban sustainability and improving overall quality of life by providing green spaces that promote physical and mental well-being, mitigate environmental issues, and foster community cohesion. However, there is a lack of methodologies that measure these benefits and provide a sustainability rating. In this study, we propose a valuable tool for measuring the sustainability level of urban parks: low (0–50%), medium (51–79%), and high (80–100%). It employs effective and affordable measures for the daily management of urban parks. It is rooted in the three pillars of sustainability: environmental, social, and economic. We have defined 19 indicators (e.g., renewable energy and energy efficiency, environmental impact on society) and 50 criteria (e.g., clean energy generation, water workshops). A multi-criteria analysis facilitated the selection process for these indicators and criteria. This methodology is developed by characterizing and systematically documenting the park's day-to-day operations. We present a case study of Cárcamos Park in Guanajuato, Mexico. Through this real-life scenario, we demonstrate our methodology's high applicability and effectiveness. The sustainability assessment of Cárcamos Park reveals a level of 57%, with the environmental pillar at 47.7%, the economic pillar at 49%, and the social pillar at 75%. The adaptability of our methodology during the design phase of new parks plays a crucial role in shaping sustainable park layouts. Park managers can apply our procedure to any park, evaluate their sustainability status, and detect areas of opportunity.

Keywords: sustainability; urban parks; green areas; sustainable cities

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1. Introduction

In urban planning and sustainability, the significance of urban parks cannot be overstated. This relevance amplifies as the world is becoming increasingly urbanized [1,2]. Population growth and migration have been the main drivers of the urban shift that has characterized the last century, and this trend is likely to continue in the coming decades [3–5]. The urban share worldwide will rise from around one-third in 1950 to approximately two-thirds in 2050. Sustainable development depends on successfully managing urban growth to create sustainable cities in developed and developing countries [6–8]. The sustainability of cities and their regeneration strategies principally focus on improving the cities' infrastructure and resilience of the urban environment [9,10]. The fundamental goal of a sustainable city is the advancement and facilitation of the long-term well-being of people and the planet through the effective use of natural resources and management of wastes while enhancing liveability through economic prosperity and social well-being within a city [11–13]. A comprehensive definition of sustainable cities and their sustainable development is provided by Roosa [14] (p. 44): "Sustainable development is the ability of physical development and environmental impacts to endure long-term habitation on the planet Earth by human and other indigenous species while providing: (1) an opportunity for environmentally safe, ecologically appropriate physical development; (2) efficient use of natural resources; (3) a framework which allows improvement of the human condition and equal opportunity for current and future generations, and; (4) manageable urban growth". Sustainable urban planning and the design of green infrastructures such as street trees, green roofs, and open green spaces like parks can contribute to reducing temperature and pollution in urban areas as well as creating habitats to protect biodiversity [15,16].

Urban parks are public places that provide essential ecosystem services, such as oxygen production, air, and water purification [17], as well as noise and air filtering. Parks create a micro-climate and give space for biodiversity protection [18]. In addition, they provide social and psychological services and promote the well-being and education of citizens, which is relevant to the livability of cities [9,19,20].

People often associate urban parks with sustainability in cities. Nevertheless, despite the apparent benefits, the park's presence alone does not automatically imply a positive impact on the environment, society, and economic viability. These spaces must offer specific characteristics that adapt to their location to provide tangible benefits [21]. Sustainable parks are different from traditional parks in three main ways: (1) they are self-sufficient in terms of efficiency in resources like fertilizers, as well as energy and water consumption with regard to reducing maintenance costs; (2) they mitigate greenhouse gas emissions to reduce environmental challenges in cities since they provide sustainable benefits inside their limited boundaries, acting as "green lungs" in their communities; and (3) they provide a habitat for native species [22]. The research of Vélez Restrepo [23] indicates that the contribution of parks, in terms of sustainability and resilience, takes into account the park's energy and water consumption and waste management.

Local sustainable management practices will have global impacts, primarily due to the forces of globalization [24,25]. In addition, local sustainable park practices act as showcases for others and can thus spread. To raise sustainability in urban parks, an increased capacity of responsible managers is essential [26]. Nevertheless, those managers often lack sufficient skills and tools to ensure that local green areas are more resilient to the challenges posed by global change [9].

Furthermore, urban green areas worldwide frequently suffer from economic challenges and are not financially self-sufficient. The economic demands of a park encompass a spectrum of financial obligations that include but are not limited to staff compensation, electricity consumption, maintenance expenses, the establishment and maintenance of green space, the provision of composting facilities, and the construction and maintenance of infrastructure and buildings. Consequently, their maintenance and sustainable development is limited [27,28]. It is therefore essential to improve the management of the parks with practical strategies and tools; continuous collecting and monitoring of information on the condition of parks is fundamental to maintaining environmental quality [29]. The high population density of the cities and the limited recreation areas put high pressure on parks and affect their sustainability. The challenge for urban park managers is to meet the needs of all visitors and still guarantee the sustainability and protection of park resources [30].

According to Dearden et al. [31] and Gavrilidis et al. [32], properly managing and protecting existing parks is more important than creating new parks. In the same way, the tools and strategies in park management are essential to reach and improve upon the goals and targets for present parks [33]. The parks must be designed considering the current and expected future climate and conditions [34]. However, cities need more information on the quantity and quality of urban parks; the existing data need to be completed and more interrelated, and a database with the parks managing information might improve their function [9]. To implement strategies for sustainability, sustainability indicators are essential since they help to measure green areas' functions comprehensively. Sustainability indicators facilitate the assessment of the level of sustainability and the understanding of areas of opportunities for decision-makers and environmental-policy-makers [29,35]. There are some presentations of methodologies to measure the sustainability of urban green areas, none of which can provide a complete picture of sustainability. Social and economic elements are given little consideration. Cranz and Boland [22] consider five elements to define a park as sustainable: native plants, permeable surfaces, ecological restoration, green infrastructure, and resource self-sufficiency. They defined park sustainability considering social and environmental elements like human and ecological health, environmental education, and wildlife protection [22]. Nevertheless, they neither considered the infrastructure and buildings installed within the park nor information on the park employees or infrastructure, including waste management infrastructure like a waste collection center. Ávila and Medina [36] address the sustainability from a socio-environmental perspective, and Morales-Cerdas et al. [35] include environmental and socio-environmental aspects by applying the following 11 environmental indicators: (1) the percentage of the area in which the protection surface was respected according to the regulations; (2) the percentage of native and exotic species in urban parks; (3) the number of trees per area (density); (4) the species structure, such as the height of trees; (5) the diameter; (6) the number of trees planted in streets; (7) the number of trees planted in street pavements; (8) the number of trees planted in avenues; (9) the soil permeability; (10) the soil biotic index; and (11) the potential of urban parks to host bird-life, for managing urban green areas to determine their environmental condition without considering the economic value. The socio-environmental perspective is critical since it relates the affecting components of visitors to conservation practices in public spaces. In addition to the participation and education of citizens and workers, we propose to include the economic situation (economic pillar) with equal weight as it may reflect efficiency in the use and consumption of resources, leading to economic self-sufficiency. Waste separation and recovering the value of the residues can generate financial resources that can be invested in the park to improve its operation.

Dizdaroglu [13] considers a complete spectrum and notes 10 core sustainable design objectives of urban parks, which are (1) providing green infrastructure; (2) creating a place for people of all ages; (3) building connected park systems within walking distance; (4) implementing water and energy conservation practices; (5) waste management; (6) promoting access to fresh, healthy, and low-cost food; (7) supporting and preserving biodiversity; (8) environmental education and stewardship through hands-on activities; (9) ensuring the long-term maintenance and management of the park; and (10) supporting disaster resilience. Within these objectives, they describe, in theoretical terms, the importance of sustainable park design and management as it broadens the scope of parks in the role of sustainable cities in helping to overcome environmental problems arising from urban sprawl. In order to measure the degree of sustainability of universities and identify their areas of opportunity, one might use the UI Green Metric World University Ranking (Green Metrics) [37]. The Green Metrics initiative, launched by the University of Indonesia in 2010, provides the result of an online survey regarding the current conditions and policies related to green campuses and sustainability in universities worldwide. Green Metrics has six criteria: setting and infrastructure, energy and climate change, waste, water, transportation, education, and research, with 51 indicators that focus on the objectives of sustainable universities. It is a simple guide to measuring and applying university sustainability. Nonetheless, nothing similar to the Green Metric World University Ranking exists for parks [38].

Our methodology focuses on integrating all components related to the operation of an urban park, which is essential for a complete survey. To this end, we have developed a scalable, flexible, and replicable tool that enables the measurement of the sustainability of urban parks. Our methodology is designed to be reproducible, low-cost, and easy to implement by anyone using collected operational data from the park. Our objective is to obtain a sustainability grade for the park and identify areas of improvement. To achieve this, we have developed a method based on three dimensions of sustainability, which we call pillars: environmental, social, and economic. These three pillars contain 50 criteria and 19 indicators that are used to characterize and gather information from day-to-day operations. Using our methodology, park managers can plan short-, medium-, and long-term environmental, social, and financial actions while tracking their progress.

Furthermore, our indicators can be used as a reference for designing new urban parks that are sustainable from the outset.

2. Methodology and Sustainability Scheme Proposal

Our methodology corresponds to a quantitative analysis of park operation data, which seeks to draw a scalable, flexible, and replicable roadmap in other parks. This procedure consists of creating a database on the park's operation, including environmental, economic, and social aspects. Konijnendijk et al. [20] define urban parks as "delineated open space areas, mostly dominated by vegetation and water, and generally reserved for public use. Urban parks are mostly larger but can also have the shape of smaller 'pocket parks'. Urban parks are usually locally defined (by authorities) as "parks" ([20], p. 2). Our methodology exhibits broad applicability across urban parks of varying sizes and diverse characteristics. However, it is important to note that there is little evidence to suggest that our methodology can be effectively adapted to small parks, lawns, sports parks, waterside parks, and similar settings. Therefore, our methodology is primarily limited to larger urban parks characterized by a diverse range of facilities and infrastructure components, including buildings and recreational areas.

Pillars, indicators, and criteria: Our methodology is based on the three pillars of sustainability: environmental, economic, and social. For facilitating the data collection and analysis, the three pillars are divided into 19 indicators that consist of 50 criteria (the database) (see Figure 1).

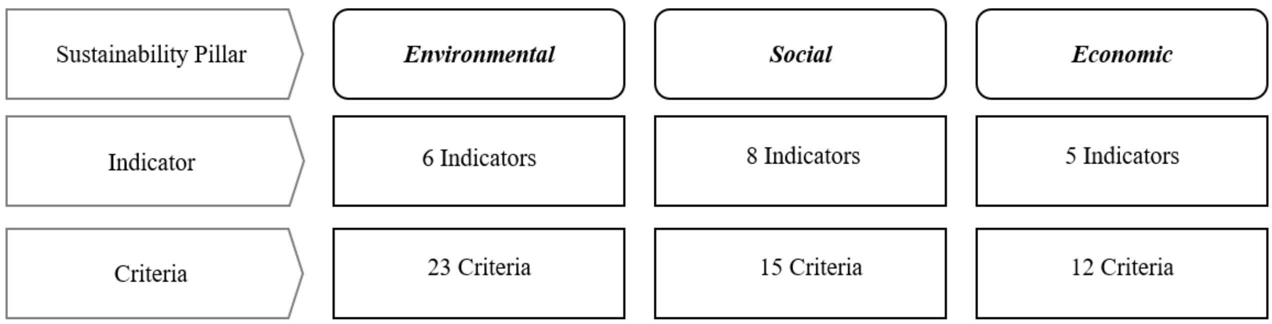

Figure 1. Sustainability scheme.

The inclusion of the specific criteria and indicators in the data collection for measuring sustainability is essential due to the following rationales: resource use (quantify and conserve resources), financial health (ensure economic viability), environmental impact (reduce ecological footprint), social well-being (enhance community and visitor experiences), biodiversity (preserve ecological integrity), resilience (adapt to environmental challenges), innovation (drive continuous improvement), equity (promote accessibility and fairness), education (engage and educate the public), and compliance (adhere to legal standards) [9,12–14]. These points, which offer a holistic view of sustainability in the park, are important for measuring sustainability and are therefore taken into account in our indicators and criteria described below.

Each pillar is evaluated equally, with one-third each, no matter the number of indicators or criteria. The highest sustainable value that an urban park can achieve is 100%.

2.1. Indicators and Criteria

The indicators represent a first differentiation of the pillars that represent specific groups or topics of the criteria.

Criteria of the same category are joined to one indicator of 19 indicators in total. The environmental pillar consists of 6 indicators and 23 criteria. The indicators are: (E1) sustainable transport, (E2) green area and biodiversity, (E3) water conservation, (E4) renewable energy and energy efficiency, (E5) waste management, and (E6) sustainable building with certification (sustainability) (see Figure 1). The social pillar consists of 8 indicators and 15 criteria. The indicators are: ((S1) exclusive maintenance staff, (S2) environmental impact on society, (S3) space for environmental education, (S4) environmental policies for the use of the green area, (S5) environmental policies for the use of the green area, (S6) environmental management system in the office, (S7) accessible entrance, and (S8) sustainable building with certification (health) (see Figure 1). Finally, the economic pillar has 5 indicators and 12 criteria. The indicators are: (EC1) sale of waste, (EC2) charging fees, (EC3) waste registration and collector control, (EC4) energy efficiency, and (EC5) sustainable building with certification (efficiency) (see Figure 1). The social pillar has the highest number of indicators (8). The environmental pillar has the highest number of criteria (23). The economic pillar has the lowest number of criteria (12) and indicators (5).

2.2. Criteria and Additional Data

The criteria represent numerical information collected by the park management on a day-to-day basis that directly influences the grade of sustainability. Some of these criteria (collected data) need additional data to be calculated (see Table 1). Those additional data do *not* have a direct impact on the level of sustainability. For example, the criterion (1) *percentage of park employees that use car mobility to go to work* is calculated from two additional data: (1) the additional data *number of park employees that use car mobility to go to work* and (2) the additional data *total number of persons* (see Figure 1 and Table 1). The 18 additional data are only required to evaluate the environmental and economic pillar criteria. No additional data are required for the social pillar criteria (see Table 1).

Table 1. Additional data used for assessing certain criteria (1, 2, 3, 4, and 5) in the indicators of the environmental pillar (E1, E2, E3, and E4) and economic pillar (EC4).

No.	Additional Data	Indicator/Criteria
1	Total number of employees	E1/1
2	Number of employees that use car mobility to go to work	E1/1
3	Total surface of the park (m^2)	E2/1, E2/3
4	Total surface of green area (m^2)	E2/1
5	Total surface of constructed and sealed area (m^2)	E2/1
6	Total number of trees in the green area	E2/3, E2/4, E2/5
7	Number of native trees	E2/4
8	Number of healthy trees	E2/5
9	Volume of treated water (m^3)	E3/3
10	Volume of water used for irrigation (m^3)	E3/3
11	Number of total bulbs in the offices	E4/1, EC4/2, EC4/3
12	Number of LED bulbs in the offices	E4/1, EC4/2, EC4/3
13	Number of total bulbs in the green area	E4/2
14	Number of LED bulbs in the green area	E4/2
15	Total energy consumption (kWh)	E4/3, E4/4, EC4/1
16	Energy produced by renewable energies	E4/3, EC4/4, EC4/1
17	Total number of electronic equipment	EC4/4
18	Number of electronic equipment that are less than five years old	EC4/4

Positive or negative impact: Criteria were determined to have a positive or negative impact on sustainability. Positive impacts were highlighted with a plus sign (+), and negative impacts have been assigned a negative sign (−).

Internal and external impacts (dependencies): Each criterion was classified according to its internal or external dependency to reveal if the park management has direct control of the value of the criterion (internal) or if the criterion cannot be directly influenced by the park management (external). The impacts or dependencies of internal control are criteria the park manager can intervene or modify, such as automatic irrigation. Those internal dependencies are marked with the letter (i+) if the impact is positive and (i−) if the impact is negative.

The criteria of external dependencies are criteria where only external forces like the government can intervene or modify, not the park management itself. For example, the criterion "presence of a lake (water body) inside the park" is marked with the letter (e+) since the decision to install a lake is external and a lake has a positive impact on sustainability. The criterion "number of park employees that use car mobility to go to work" was assigned with the impact "i−" since this criteria can be influenced internally by the park management (i, Internal) and has a negative (−) impact on sustainability.

Sustainability degree: The first step in achieving the sustainability degree is assigning the value for each criterion. Those values range from 0 to 100 points, with 100 being the highest possible. For a positive impact criterion (+), 100 is the best sustainability value. In the case of a negative impact criterion (−), 0 is the best value for a high sustainability assessment.

The indicator weights result from the average of the corresponding criteria values. Then, the weights of the pillars are computed as the average of their indicator values. The final sustainability degree is calculated by averaging the values of all three pillars, with each pillar participating equally with one-third.

According to the appraisal and evaluation strategies proposed by Dodgson et al. [39] (Chapter 2, pages 9–13), the decision-making process that helped us to define the point range of the degrees of sustainability (see Table 2) was as follows: (1) identifying objectives, (2) identifying options for achieving the objectives, (3) identifying the criteria to be used to compare the options, (4) analysis of the options, (5) making choices, and (6) feedback [39].

The three sustainability levels and their point range are defined as: (1) low sustainability for those with a total score between 0 and 50, (2) medium sustainability with a score between 51 and 79, and (3) high sustainability for a score between 80 and 100 (see Table 2).

Table 2. Degrees of sustainability in parks.

Point Range	Sustainability
0–50	Low sustainability
51–79	Medium sustainability
80–100	High sustainability

2.2.1. Criteria in the Environmental Pillar

The environmental pillar contains 6 indicators and 23 criteria (see Table 3).

Table 3. Sustainability values: environmental pillar with its respective *impact* (internal i or external e, positive + or negative −), *current park value* (recent sustainability value of Cárcamos Park, Mexico), and *parks improvement value* (percentage of potential improvement considering only internal impacts that can be influenced by park managers).

Indicator (E1–E6), Criteria (1, 2, . . . , 6)	Impact Internal (i), External (e), Positive (+), Negative (−)	Current Park Value	Parks Improvement Value
E1: Sustainable transport		**8.8**	**50.0**
1. Percentage of park employees that use car mobility to go to work	i−	35.0	100.0
2. Kilometers driven per day per employee to go to the park	e−	0.0	0.0
3. Low-emission motorised transport	e+	0.0	0.0
4. Bicycle infrastructure	i+	0.0	100.0

Table 3. *Cont.*

Indicator (E1–E6), Criteria (1, 2, . . . , 6)	Impact Internal (i), External (e), Positive (+), Negative (−)	Current Park Value	Parks Improvement Value
E2: Green area and biodiversity		**64.4**	**92**
1. Percentage of green area	e+	60.0	60.0
2. Pollinator garden	i+	100.0	100.0
3. Trees per hectare	i+	20.2	100.0
4. Percentage of native trees	i+	54.6	100.0
5. Percentage of healthy trees	i+	87.3	100.0
E3: Water conservation		**33.3**	**66.6**
1. Presence of a lake (water body) inside the park	e+	100.0	100.0
2. Automatic irrigation	i+	100.0	100.0
3. Use of treated water for irrigation	e+	0.0	0.0
4. Percentage of water treated after use	e+	0.0	0.0
5. Rainwater harvesting systems	i+	0.0	100.0
6. Water-saving devices	i+	0.0	100.0
E4: Renewable energy and energy efficiency		**96.5**	**100.0**
1. Percentage of LED lighting in the offices	i+	92.0	100.0
2. Percentage of LED lighting in the green area	i+	100.0	100.0
3. Clean energy generation	i+	94.0	100.0
4. Emission reductions from clean energy generation	i+	100.0	100.0
E5: Waste management		**83.3**	**100.0**
1. Waste collection and separation service	i+	100.0	100.0
2. Organic waste management (composting)	i+	100.0	100.0
3. Recycling program	i+	50.0	100.0
E6: Sustainable building with certification (sustainability)		**0.0**	**0.0**
1. Sustainable building with green building certification	e+	0.0	0.0
Total value of environmental pillar		**47.7**	**68.1**

Sustainable transport indicator (E1) considers four different criteria, and the value of this indicator consists of their average. Criterion (1) *percentage of park employees that use car mobility to go to work* refers to the percentage of workers who come to the park with their car that runs on fossil fuels. This percentage results from the two additional data: *total number of employees* and *number of employees that use car mobility to go to work*. This resulting percentage equals the number of points for this criterion. Criterion (2) *kilometers driven per day per employee to go to the park* refers to the distance between work and home that park employees must travel and includes only fossil fuel cars. The daily trips should be optimized and be a maximum of 7 km from home to work to accelerate the urban development solution and sustainable mobility [40]. Criterion (3) *low-emission motorized transport* represents the possibility of reaching the park with a low-emission means of transport (e.g., public transport or organizing car sharing). The existence of a low-emission transport to the park leads to 100 points. The contrary leads to zero points. Criterion (4) *bicycle infrastructure* refers to the availability of bicycles in the park to encourage their use as an alternative means of transportation. If bicycles are available inside the park, 100 points; if not, 0 points. *Green area and biodiversity indicator* (E2) considers the values of five criteria whose average leads to the indicator value: Criterion (1) *percentage of green area* is determined using three additional data: the *total surface of the park*, the *total surface of green area*, and *total surface of constructed and sealed area* (see Table 1). The number of points available in this indicator is equal to the percentage of the park's green area. Criterion (2) *pollinator garden* evaluates if there is a pollinator garden inside the park. If the park counts with a pollinator garden, this equals 100 points. No pollinator garden equals 0 points. Criterion (3) *number of trees per hectare* takes into account a minimum number of trees per hectare in parks. Therefore, we adhered to the guidance stipulated by the National Forestry Agency in Mexico (CONAFOR), which recommends a tree density of 625 trees per hectare for parks [41], which refers to one tree every four meters. This criterion could be adapted to the recommended data from organizations outside Mexico. The points that can be achieved for this criterion are a percentage of this recommended number of trees per hectare. The value of criterion (4) *percentage of native trees* results from the percentage of native trees (calculated from two additional data: *total number of trees* and the *number of native trees*, see Table 1) from the recommended of 80% of native trees (and maximum 20% exotic trees), according to Sánchez and Artavia [42]. Criterion (5) *percentage of healthy trees* is calculated including the additional data of the *total number of trees* and *number of healthy trees* (see Table 1. The percentage of healthy trees in the park equals the score of this criterion. The average of all criteria leads to the value of this indicator.

Water conservation indicator (E3) considers six criteria. Criterion (1) *presence of a lake (water body) inside the park* scores 100 points if the park has a lake; no lake scores zero points. Criterion (2) *automatic irrigation* scores 100 points if the park uses nutrient-rich water from the lake to irrigate green areas. Criterion (3) *use of treated water for irrigation* leads to 100 points if the park uses treated water for irrigation, regardless of where the water was treated, outside or inside the park. Criterion (4) *percentage of water treated after use* refers to the percentage of irrigation water that was treated after being used in bathrooms or other facilities, etc. This percentage equals the number of points. Two additional data are necessary for this criterion: *volume of treated water* and *volume of water used for irrigation*. Criterion (5) *rainwater harvesting systems* means that installing a water-capturing facility leads to 100 points; if the park lacks such a technology, zero points are awarded. Criterion (6) *water-saving devices* considers installing water-saving technologies in bathrooms: its percentage equals the number of points.

Renewable energy and energy-efficiency indicator (E4) considers four criteria. Additional data (11–16) are necessary to appraise the criteria of this indicator (see Table 1). Their average equals the value of this indicator: criterion (1) *percentage of LED lighting in the offices* refers to the percentage of LED lamps installed in the buildings equals the number of points. The two criteria that lead to this value are the total number of bulbs and the number of LED bulbs installed in the buildings. Criterion (2) *percentage of LED lighting in the green area* refers to the percentage of LED lamps installed in the green area equals the number of points (the total number of bulbs and the number of LED bulbs installed in the green areas are the two criteria that lead to this value). Criterion (3) *clean energy generation* refers to the generation of green energy by renewable energies like solar or wind. Criterion (4) *emission reductions from clean energy generation*; their present percentage leads to the number of points.

Waste management indicator (E5) evaluates the management of residues inside the park and considers three criteria. The criterion (1) *waste collection and separation service* indicates if the park offers a recycling center where recyclable waste like paper, metal, glass, batteries, or PET (polyethylene terephthalate) are collected and separated. The presence of such a service leads to 100 points; the contrary equals zero points. Criterion (2) *organic waste management (composting)* leads to 100 points if the organic waste from the park is collected and composted. Criterion (3) *recycling program* leads to 100 points if a recycling program helps prevent waste and regulates its treatment in a sustainable way. No recycling program in the park would lead to zero points.

Sustainable building with certification (sustainability) indicator (E6) includes one criterion, criterion (1) *sustainable building with green building certification*. If the park has a building, it must have a green building certificate, such as LEED, Passive House, or BREEAM [43,44]. In order to obtain 100 points in this criteria, a green building certificate guarantees the sustainability of the building [45]. No certificate leads to 0 points. If the park has no building, this indicator counts for 100 points. If the park has more than one building, the percentage of buildings with green certificates equals the number of points.

2.2.2. Criteria in the Social Pillar

The social pillar holds 8 indicators and 15 criteria.

exclusive maintenance staff indicator (S1) takes into account one criterion: criterion (1) *Exclusive maintenance staff*, which refers to employees that take care of and maintain the sustainable aspects of the park. At least one employee who takes care of the sustainable aspects inside the park, reflected by the three pillars (environmental, social, and economic), leads to 100 points.

Environmental impact on society indicator (S2) considers one criterion: criterion (1) *environmental education events* refers to environmental education events offered by the park, which should be at least 12 events per year or one per month. That means 12 events per year equals 100 points; 6 events leads to 50 points; and no events leads to zero points.

Space for environmental education indicator (S3) considers one criterion: criterion (1) *space to promote environmental education* refers to the existence of a dedicated space for environmental education activity. In order to achieve the highest score, the park has such an area available, which can be, for example, a botanical garden or a butterfly house.

Environmental education workshops indicator (S4) takes into account six criteria, which are public information lectures or workshops on the most important environmental issues for everyone: criterion (1) *biodiversity workshops* includes talks and/or activities on biodiversity, criterion (2) *waste workshops* includes talks/activities on resources and residues, criterion (3) *air quality workshops* includes talks and/or activities on air quality, criterion (4) *soil workshops* includes talks/workshops on the importance of the soil, criterion (5) *water workshops* represents talks and/or activities on water protection and criterion (6) *climate workshops* represents workshops on the importance of climate change. One talk and/or activity on a respective topic equals 100 points. No activity equals zero points. The average of all criteria leads to the value of the indicator.

Environmental policy for the use of green area indicator (S5) considers criterion (1) *environmental policies for use of green area*. If the park counts with environmental policies like the visitors' behavior in an environmentally friendly way (avoiding single-use containers or giving instructions on how to take care of flora and fauna inside the park), it leads to 100 points. No established environmental policy leads to zero points.

The *environmental management system in office indicator* (S6) consists of criterion (1) *environmental management system in office*. If the park has implemented a program, this criterion obtains the maximum score of 100 points.

Accessible entrance indicator (S7) considers three criteria defining the accessibility of the park to all citizens. Criterion (1) *free access (no entrance fee)* means that access to the park is free and no entrance fee is charged. Criterion (2) *open 7 days a week* means that the park opens every day (365 days/year), and criterion (3) *open at least 10 h a day* considers that the park is available for the public for a minimum of 10 h per day. In conclusion, all three criteria would lead to 100 points; if the criteria are not fulfilled, this equals to zero points for the respective criteria. Their average leads to the value of this indicator.

Sustainable building with certification (health) indicator (S8) includes criterion (1) *sustainable building for healthy living/working*. If the park has a building, it must have a green building certificate, such as LEED, Passive House or BREEAM [43,44], in order to obtain 100 points in this criterion since a green building certificate guarantees a healthy atmosphere inside the building [45]. No certificate leads to 0 points. If the park has no building, this indicator counts for 100 points. If the park has more than one building, the percentage of buildings with a green certificate equals the number of points.

2.2.3. Criteria in the Economic Pillar

The economic pillar contains 5 indicators and 12 criteria that consider economic resources.

Economic resources generated from *sale of waste indicator* (EC1) considers two criteria of economic value: (1) *sale of paper, carton, plastic, aluminum, iron, newspaper, electronic, tetra-pack, organic waste, and glass.* Plastics refers to PET since it is economically the most important [46,47]. For each residue in the list, the park receives 10 points. If all waste types are sold, 100 points are achieved. Criterion (2) *alkaline batteries* shows the importance of collecting alkaline batteries and guaranteeing their adequate recycling. Both criteria are of external impact since the park management cannot influence the price of residues. The average of all criteria values leads to this indicator's value.

Charging fees indicator EC2 considers three criteria. Criterion (1), *entrance fee*, indicates if the entrance to the park is free of charge. Criterion (2) *workshop fee* indicates if the park can generate economic revenue by organizing and charging for workshops. Criterion (3) *rent space fee* indicates if the park can generate economic revenue by charging for the rent of special areas inside the park. All three criteria lead to zero points if no fees are charged since this would be an economic disadvantage.

Waste registration and collector control indicator (EC3) considers two criteria: criterion (1) *waste registration* of collected and separated waste at the collection center, including the type of waste, the weight (kg), and the distance (m) from where they come from; the presence of a waste registration folder (analog or digital) leads to 100 points, and no continuous waste registration leads to zero points; and criterion (2) *authorized waste collector*; the park obtains 100 points if the waste collector is legally authorized and counts with all necessary permits to manage recyclable waste. The average of both criteria leads to the indicator's value.

Energy-efficiency indicator (EC4) considers four criteria: criterion (1) *clean energy generation* refers to economic savings through renewable energy generation like solar, wind, geothermic, and biomass plants. The percentage of green energy generation leads to the number of points. Criterion (2) *percentage of LED-illumination in offices* refers to the percentage of highly efficient illumination (LED) in the offices that leads to the number of points. Criterion (3) *percentage of LED-illumination in the green area*, refers to the percentage of highly efficient illumination (LED) in the green area leading to the corresponding number of points. Criterion (4) *efficient electronic equipment (not older than 5 years)* means that recent energy-efficient devices and equipment like pumps and computers, printers, and refrigerators that are less than five years old can lead to economic benefits; the percentage of the respective installations leads to the number of points. All criteria of this indicator need additional data (see Table 1 to determine the criteria of this indicator. The indicator's value represents the average of all criteria values.

Sustainable building with certification (efficiency) indicator (EC5) includes one criterion: (1) *sustainable building for energy efficiency and cost-savings*. If the park has a building, it must have a green building certificate, such as LEED, Passive House, or BREEAM [43,44], in order to obtain 100 points in this criterion since a certificate guarantees cost savings through energy savings and cost efficiency [48]. No certificate leads to 0 points. If the park has no building, this indicator counts for 100 points. If the park has more than one building, the percentage of buildings with a green certificate equals the number of points. In the following section, we demonstrate the applicability of our methodology and its ease of assessment using real operational data from Cárcamos Park.

3. Results

This Section presents our methodology's application in Cárcamos Park in the city of Leon in Guanajuato, Mexico. Cárcamos Park was selected as the study site due to unrestricted access to the entirety of the park's operational dataset. First, we describe the park we used as a case study and then explain the captured operational data. Finally, we show the sustainability values obtained for each criterion, indicator, and pillar and calculate the sustainable degree of this case study park. The study's outcome identified the opportunities for improving the sustainability level of Cárcamos Park.

3.1. Case Study Cárcamos Park, Mexico

In order to test the applicability of our methodology, we introduced the real operational and maintenance data from Cárcamos Park to our datasheet. Cárcamos Park is located in the City of León in Guanajuato, Mexico (see Figure 2). Cárcamos Park has a total area of 116,074.99 m^2, of which the green area occupies 60% with 1457 trees; the built-up area occupies 4%, and a lake occupies 36% of the surface area.

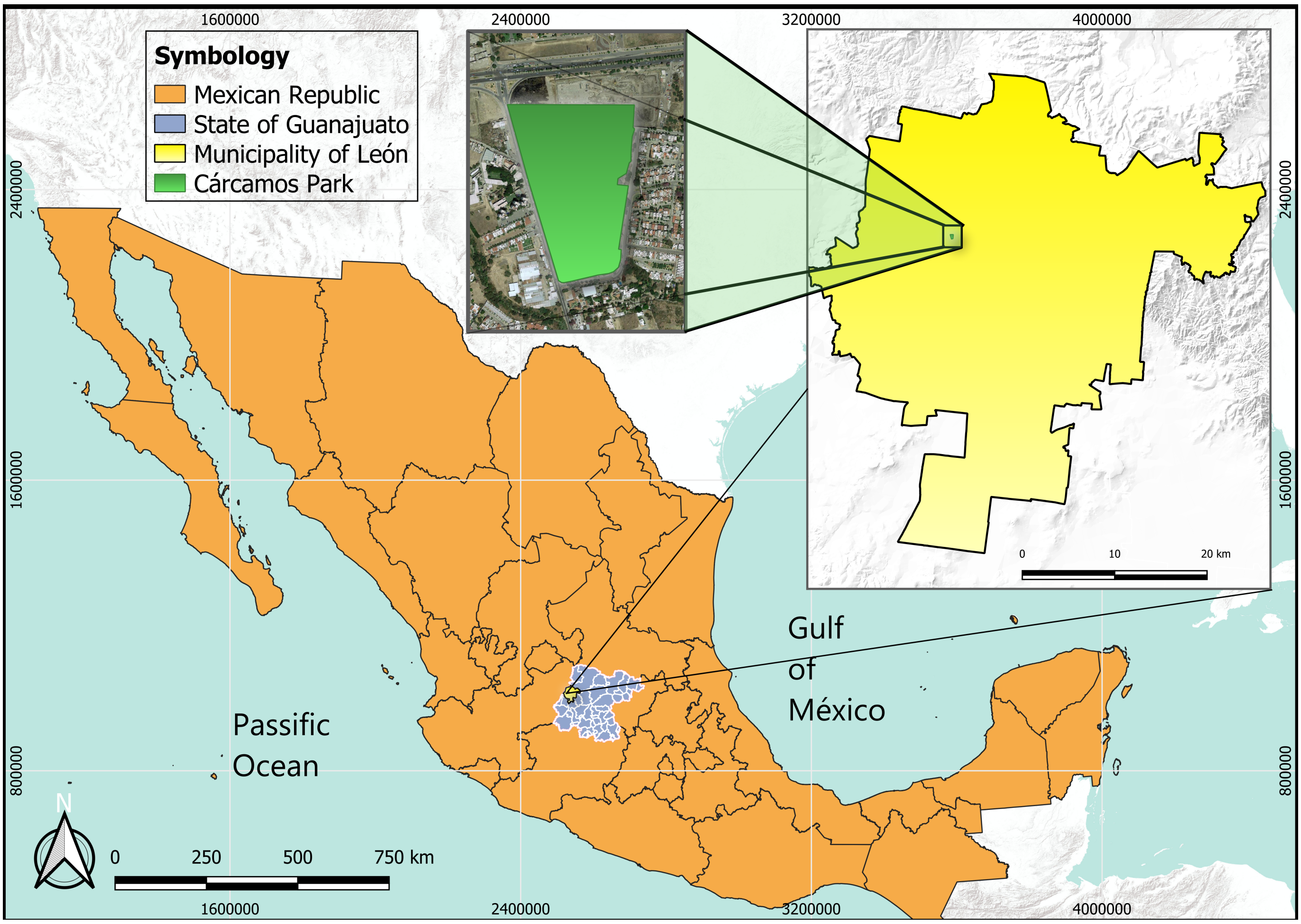

Figure 2. Location of Cárcamos Park in Mexico. Source: Own elaboration using QGis software and INEGI layers [49].

Cárcamos Park serves a dual purpose. It provides ample public green space and accommodates buildings with government offices in the park's southern area. The presence of government employees in the park has numerous benefits, particularly in data collection and monitoring.

The government building inside the park spans two floors, which shelters a team of 20 employees who work weekdays from Monday to Friday. In addition to this, the park features an area dedicated to promoting environmental education and a collection center for citizens to drop off waste materials with a monetary value. These facilities are open every day of the year from 6:00 a.m. to 8:00 p.m., offering park visitors 14 h of access per day. The park also employs a full-time maintenance worker to tend to the green space, while the government office staff stationed on-site split their duties between the botanical garden and the collection center.

We have carefully compiled all relevant operation data of Cárcamos Park and summarized it in a comprehensive data sheet with 50 criteria and 18 additional data (see Table 1). In order to ensure a complete understanding of the park's performance, we found it necessary to collect information over one year spanning all seasons, including changing seasons and situations such as holiday seasons, rainy seasons, and droughts. Thus, we incorporated all operational data from January to December 2020 to generate the database. Although 2020 was atypical, marked by the global SARS-COVID-19 pandemic, it provided an opportunity to evaluate the park's behavior from a baseline level. Additionally, with the reactivation of activities in August, the database facilitated an observation of the movements and changes in the park's operating parameters.

3.2. Sustainability Degree of the Case Study, Cárcamos Park, Mexico

This proposal presents the determination of the degree of sustainability assigned for Cárcamos Park in Mexico. It identifies the percentage of potential opportunities for enhancement for park sustainability (see Figures 3–5).

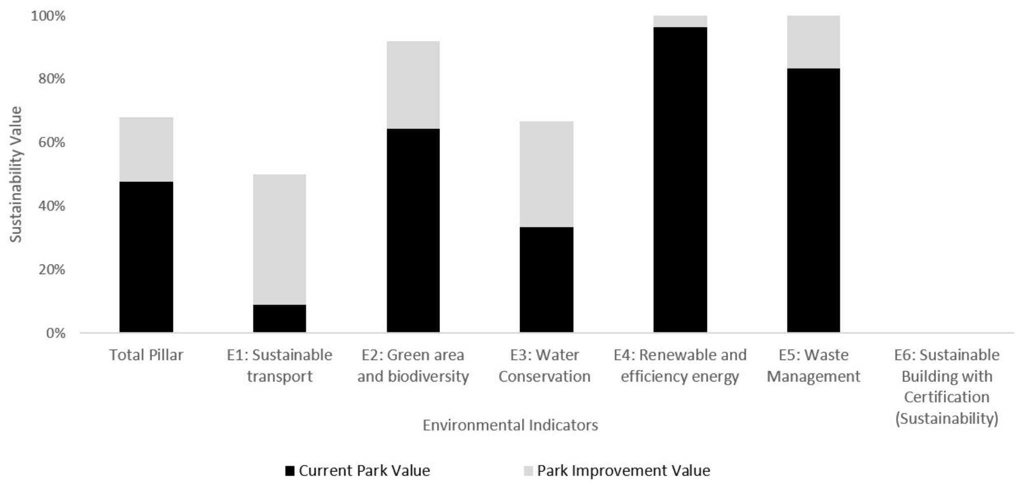

Figure 3. Environmental pillar. Sustainability value obtained per indicator for Cárcamos Park, Mexico. *Current park value* (recent sustainability value of Cárcamos Park, Mexico); *parks improvement value* (percentage of potential improvement considering only internal impacts that can be influenced by park managers).

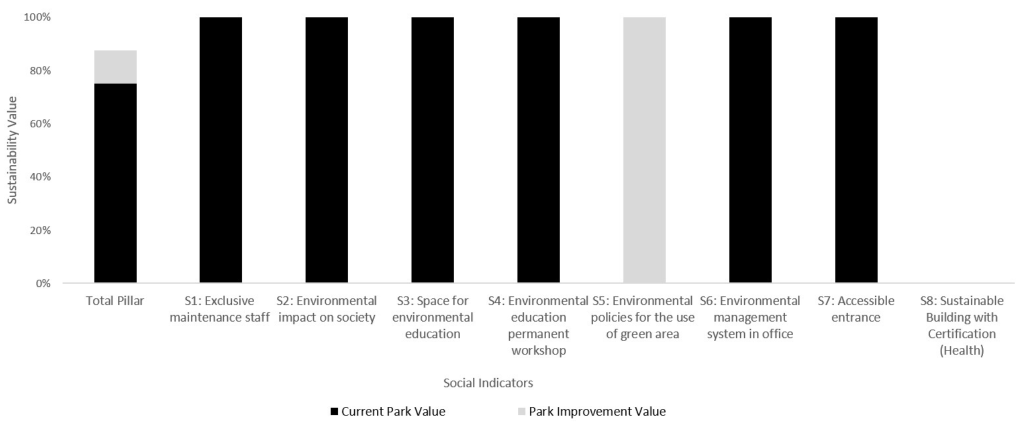

Figure 4. Social pillar. Sustainability value obtained per indicator for Cárcamos Park, Mexico. *Current park value* (recent sustainability value of Cárcamos Park, Mexico); *parks improvement value* (percentage of potential improvement considering only internal impacts that can be influenced by park managers).

Once the database with information for each of the 50 criteria and 18 additional data of Cárcamos Park was completed, we determined the values for the criteria. The weights for the indicators and pillars of Cárcamos Park resulted from summing the criteria´s values and taking their average (see Tables 3–6 and Figures 3–5).

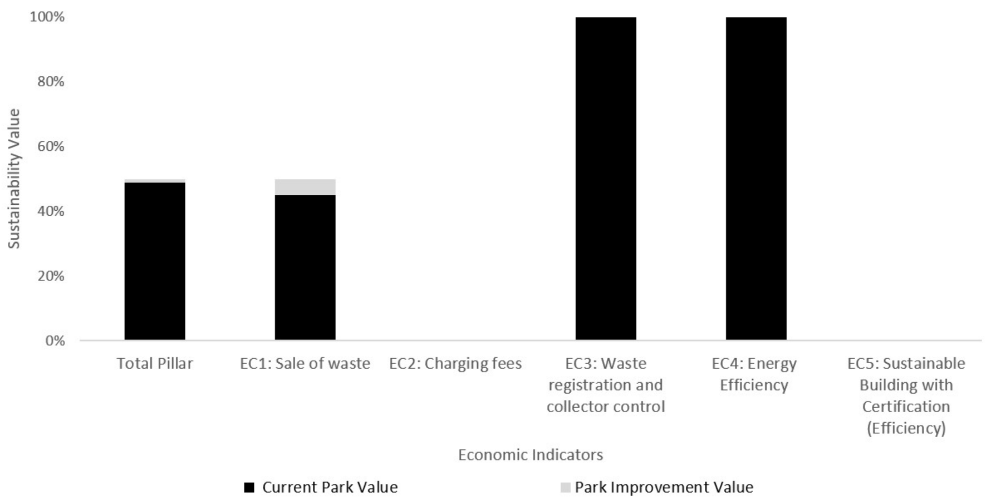

Figure 5. Economical pillar. Sustainability value obtained per indicator for Cárcamos Park, Mexico. *Current park value* (recent sustainability value of Cárcamos Park, Mexico); *parks improvement value* (percentage of potential improvement considering only internal impacts that can be influenced by park managers).

Table 4. Sustainability Values: social pillar with its respective *impact* (internal i or external e)(positive impact + or negative impact −), *current park value* (recent sustainability value of Cárcamos Park, Mexico), and *parks improvement value* (percentage of potential improvement considering only internal impacts that can be influenced by park managers).

Indicator (S1–S8), (1, C.; 2; ; 6)	Impact Internal (i), External (e), Positive (+), Negative (−)	Current Park Value	Parks Improvement Value
S1: Exclusive maintenance staff		**100.0**	**100.0**
1. Exclusive maintenance staff	e+	100.0	100.0
S2: Environmental impact on society		**100.0**	**100.0**
1. Environmental education events	i+	100.0	100.0
S3: Space for environmental education		**100.0**	**100.0**
1. Space to promote environmental education	i+	100.0	100.0
S4: Environmental education workshop		**100.0**	**100.0**
1. Biodiversity workshops	i+	100.0	100.0
2. Waste workshops	i+	100.0	100.0
3. Air quality workshops	i+	100.0	100.0
4. Soil workshops	i+	100.0	100.0
5. Water workshops	i+	100.0	100.0
6. Climate change workshops	i+	100.0	100.0
S5: Environmental policies for the use of green area		**0.0**	**100.0**
1. Environmental policies for use of green area	i+	0.0	100.0
S6: Environmental management system in office		**100.0**	**100.0**
1. Environmental management system in office	i+	100.0	100.0

Table 4. *Cont.*

Indicator (S1–S8), (1, C.; 2; ; 6)	Impact Internal (i), External (e), Positive (+), Negative (−)	Current Park Value	Parks Improvement Value
S7: Accessible entrance		**100.0**	**100.0**
1. Free access (no entrance fee)	e+	100.0	100.0
2. Open 7 days a week	e+	100.0	100.0
3. Open at least 10 h per day	e+	100.0	100.0
S8: Sustainable building with certification (health)		**0.0**	**0.0**
1 Sustainable building for healthy living/working	e+	0.0	0.0
Total value of social pillar		**75**	**87.5**

Table 5. Sustainability values: economic pillar with its respective *impact* (internal i or external e) (positive impact + or negative impact −), *current park value* (recent sustainability value of Cárcamos Park, Mexico), and *parks improvement value* (percentage of potential improvement considering only internal impacts that can be influenced by park managers).

Indicator (EC1-EC5), Criteria (1, . . . , 4)	Impact Internal (i), External (e), Positive (+), Negative (−)	Current Park Value	Parks Improvement Value
EC1: Sale of waste		**45**	**50**
1. Sale of paper, carton, plastic, aluminium, iron, newspaper, electronic, tetra-pack, organic waste, and glass	i+	90.0	100.0
2. Alkaline batteries	i+	0.0	100.0
EC2: Charging fees		**0.0**	**0.0**
1. Entrance fee	e+	0.0	0.0
2. Workshop fee	e+	0.0	0.0
3. Rent space fee	e+	0.0	0.0
EC3: Waste registration and collector control		**100.0**	**100.0**
1. Waste registration	i+	100.0	100.0
2. Authorised waste collector	i+	100.0	100.0
EC4: Energy efficiency		**98.0**	**100.0**
1. Clean energy generation	i+	100.0	100.0
2. Percentage of LED-illumination in offices	i+	92.0	100.0
3. Percentage of LED-illumination in green area	i+	100.0	100.0
4. Efficient electronic equipment (not older than 5 years)	i+	100.0	100.0
EC5: Sustainable building with certification (efficiency)		**0.0**	**0.0**
1. Sustainable building for energy efficiency and cost-savings	e+	0.0	0.0
Total value of economic pillar		**49**	**50**

Tables 3–6 show the sustainability values of the individual pillars (environmental, social, and economic) with their respective impact (internal i or external e, positive + or negative −), their current park value (recent sustainability value of Cárcamos Park, Mexico), and their parks improvement value (percentage of potential improvement considering only internal impacts that can be influenced by park managers).

Table 6. Sustainability value obtained per pillar for Cárcamos Park: *current park value* and *parks improvement value* (internal criteria that can be changed by the park management).

Pillar	Current Park Value	Parks Improvement Value
environmental pillar	47.7	68.1
social pillar	75	87.5
economic pillar	49	50
Total value	**57.2**	**68.5**

The Figures 3–5 demonstrate the sustainability values of the individual pillars, which have been assessed per indicator for Cárcamos Park, Mexico; the current park value represents the recent sustainability value of Cárcamos Park, and the parks improvement value refers to the percentage of the potential improvement considering only the internal impacts (i). These points can be influenced directly by the park managers. The indicators (E6) (sustainability) (Figure 3), (S8) (health) (Figure 4), (EC2) charging fees, and (EC5) (efficiency) (Figure 5) do not show any sustainability value nor have a park improvement value since the criteria of these indicators (E6, S8, EC2, and EC5) cannot be influenced by the park managers of Cárcamos Park.

Figure 6 shows the total sustainability values of all three pillars and the three individual sustainability values obtained per pillar for Cárcamos Park, México. The pillar of the highest sustainability value is the social pillar, with 75%, and the pillar of the lowest is the environmental pillar, with 47.7%. The sustainability values of both pillars, the environmental pillar (47.7%) and the economic pillar (49%), are in the range of low sustainability (see Table 2). The average of all three pillars increased the total value of sustainability. Cárcamos Park resulted in a final degree of sustainability of 57.2%, which is classified as medium sustainable (see Table 2).

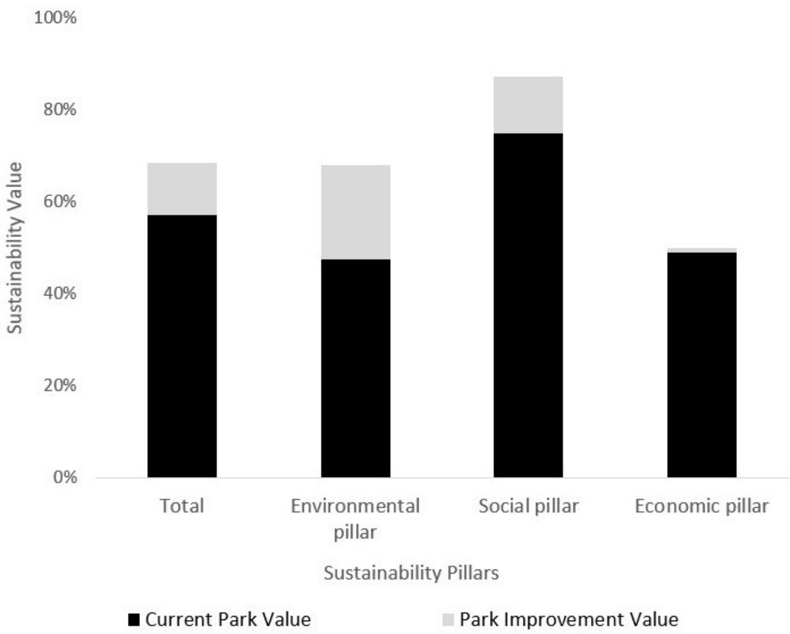

Figure 6. Total sustainability value and individual sustainability values obtained per pillar for Cárcamos Park, Mexico.

Table 3 demonstrates the sustainability values of the criteria and indicators for the environmental pillar with 47.7%, Table 4 for the social pillar with 75%, and Table 5 for the economic pillar with 49% sustainability weight. Tables 3–5 also show the respective impact values and the current sustainable park value of Cárcamos Park. The *current park value* is generated from the average of the values of the respective criteria of each indicator.

The park's improvement value is determined by considering internal and external impacts. The park management only influences the internal impacts (i), which is why these are included in the *parks improvement value*. The park management does not directly influence the external impacts (e), which is why the values from criteria with external impacts are not included in the *parks improvement value*. In order to enhance this value, external sources from the park administration, like the municipal or federal government, have to take action.

In the environmental pillar (see Table 3), the indicator with the lowest *current park value* is *sustainable building with green building certification* with 0%. The indicator with the highest *current park value* is *renewable energy and energy efficiency* with 96.5%. None of the indicators reached the highest reachable value of 100. In the same Table 3, the *parks improvement value* of the indicator *(sustainability)* is zero (0) since it is of external impact, while the indicators *renewable energy and energy efficiency* and *waste management* both have a parks improvement value of 100; both are of internal impact.

In the social pillar (see Table 4), the lowest indicators are *environmental policies for the use of green area* with 0% and *(health)* also with 0%. The other indicators all had a current park value of 100%: *exclusive maintenance staff*, *environmental impact on society*, *space for environmental education*, *environmental education workshop*, *environmental management system in office*, and *accessible entrance* .

In the economic pillar (see Table 5), the lowest indicators are *charging fees* and *(efficiency)*, both with 0%. The highest valued indicators are *waste registration and collector control* with 100% and *energy efficiency* with 98%.

A low sustainable value indicates a high area of opportunity. Considering that the pillar with the lowest sustainability level is the environmental pillar with 47.7%, we have identified the indicators with the most significant potential for improvement as follows: E1) *sustainable transport*, (E2) *green area and biodiversity* , (E3) *water conservation*, and (E6) *(sustainability)*.

In second place, the economic pillar obtained a sustainability value of 49%. The indicators *charging fees* (EC2) and *(efficiency)* (EC5) both have the lowest current park value of 0% since the Cárcamos Park charges no fees (entrance, workshop, or rent-space fees) and sustainable construction criteria are not applied. The other areas of opportunity are economic resources generated from the sale of waste (EC1). The park currently collects, separates, and sells 11 types of recyclable materials without considering resale value.

The social pillar (see Table 4) with 75% was the pillar of highest sustainability. Here, the most significant areas of opportunity are *environmental policies for the use of green area* (S5) and *(health)* (S8), both with 0% current park value, since Cárcamos Park has no environmental policy in favor of green spaces. The buildings have no green building certification.

The total sustainability value and the sustainability value obtained for each pillar for Cárcamos are shown in Figure 6. The total sustainability score is determined by summing the points earned by each pillar. In this case study, the park received an overall value of sustainability of 57.2%, indicating a medium level of sustainability with a potential for improvement up to 68.5%. The 31.5% that is missing for 100% sustainability is due to the external factors (e+ or e−) that the park administration cannot change. Only internal impacts (i+ or i−) are factored in the parks improvement value since the park management can directly influence those impacts. Our results appraise a significant opportunity to enhance the sustainability of Cárcamos Park and provide a reference for park managers of Cárcamos parks, helping them in decision-making, prioritizing action implementation, and even justifying requests for economic resources (see Figure 6).

After presenting the results of our methodology's application at Cárcamos Park, the forthcoming section will entail a comparative evaluation of our methodological framework in relation to alternative approaches. This examination will underscore its distinctive strengths while also addressing any potential weaknesses.

4. Discussion

In this section, we compare our methodological framework to alternative approaches and discuss its inherent advantages and potential limitations.

Many studies evaluate the perception and satisfaction of urban parks and the experiences and emotions produced within these green spaces, considering the size of the park, the vegetation, the convenient infrastructure, the perception of natural scenery, the conservation of equipment and nature, and the cleanliness of the environment [10,50,51]. While these studies focus mainly on visitor attraction and the appreciation of nature, it is equally essential to consider the parks' contribution to sustainability. Other authors have addressed the issue, attempting to establish the criteria necessary to strike a balance between the essential inputs to the operation of city parks and their benefits: Ávila and Medina [36], for example, analyze different perspectives based on the social-environmental aspects to develop sustainability without including the economic factors. Morales-Cerdas et al. [35] applied 11 environmental indicators for urban green areas to determine the environmental conditions as a tool for urban management, disregarding the importance of the park's economy.

Guerrero and Culós [52] applied six criteria that grouped ten indicators at two case study parks in Argentina. The requirements are reference indicators (the area covered by vegetation and sustainable human load), holistic indicators (the ecological function and heritage index), cause and effect indicators (the depredation of the urban park), projecting indicators (the tourist demand and projected municipal investment in parks), risk and uncertainty indicators (the natural vulnerability and heritage vulnerability), and control and management indicators (the integrated management of the park). Vélez Restrepo [23] shows a conceptual and analytical approach to the sustainability of urban parks and green areas and proposes the construction of a sustainability index based on three principles: (1) the ecological functionality with one indicator, (2) the economy and environmental management of resources with five indicators, and (3) social functionality with three indicators. The main difference compared to our research is that Vélez Restrepo [23] only uses nine indicators, which, in our view, are too abstract and superficial, making it almost impossible for park managers to use them to determine the park's sustainability index and to identify its areas of opportunity.

Instead, our methodology takes into account three pillars: the environmental pillar, the social pillar, and the economic pillar, with each being given equal importance as all three pillars play an essential role in the management of parks. City parks usually depend on the governmental budget, which can be limited. Undoubtedly, economic self-sufficiency can be achieved, for example, through the application of circular economy strategies: Stahel [53] or Geisendorf and Pietrulla [54]. We have included these strategies in our methodology, and park managers can use them as a guide to becoming more sustainable from an environmental, social, and financial perspective. Progressive urban park management must consider and maintain a balance between these three global pillars. This balance was not considered in the reviewed papers and reports, embedded within an easy-to-apply proposal that guides through the necessary operational data represented by our operational criteria (and *additional data*).

Our proposal includes 19 indicators, 50 criteria, and 18 additional data representing easy-to-collect data from the park management (see Table 1). We include data that other researchers do not consider:

1. The means of transport for employees must be taken into account. If employees come to the park by car, this harms the sustainability index. If they arrive instead on foot, by bike, or by public transport, the impact on sustainability would be positive.
2. We include waste management. It is vital that a sustainable park offers visitors a waste separation infrastructure and a waste collection center. Organic waste may end up in the compost as fertilizer for the park's greenery areas. Other waste like metal or PET can be sold and help to improve the park's economy.
3. A sustainable park needs environmental policies that give instructions for using green areas. Policies for saving water and energy are necessary and encourage

the sustainable behavior of park visitors and employees and are beneficial for the sustainable development of the park ([55,56]).
4. Another critical area of sustainability is energy efficiency. Here, we must consider using (a) renewable energies such as sun, wind, or biomass; and (b) illumination in the park, green spaces, and offices. The energy consumption caused by the illumination is an essential issue for a sustainable approach [57].
5. Our methodology includes the level of biodiversity as an indicator to define the sustainability of a park. The reason is that even small green spaces such as parks can include biodiversity if they provide water bodies (ponds or lakes) and green spaces nearby, creating a natural green space network [58].
6. We include the proportions of native and exotic species and their health conditions since local healthy species have to be favored [42]. Identifying tree species is a relatively easy task that an observant park employee can accomplish as the trees remain visibly in place.
7. Our methodology also integrates the maintenance workforce and the environmental impact on society through environmental education, and city parks can help reduce crime in their sphere of influence [59].
8. Our proposal includes information on the space occupied by buildings or parking facilities, which have a negative impact since they reduce the permeable area, increase waste generation, and raise energy consumption [60].
9. Our proposal includes the sustainability status of buildings inside the park. Buildings with green building certification or rating tools lead to environmental, economic, and social benefits due to their sustainable construction materials and energy efficiency [44,48].
10. Our methodology considers the economic aspects separately from the social and environmental aspects, seeking economic self-sufficiency from the services that the park can provide to the citizens, not only by saving money efficiently but also by generating money from selling recyclable waste collected and separated at a collection center inside the park, offering workshops and renting space inside the park.

Sturiale and Scuderi [61] merge the economic and social aspects to "eco-social". They consider the dimensions of sustainable development to contribute to promoting a governance model for the city called "eco-social-green". Indeed, the economic and the social aspects are strongly related in some ways. For example, Cárcamos Park does not generate any economic resources from the visitors since no fees are charged inside the park. For this reason, the current park value generation of financial help from the *charging fees* (EC2) is zero. It is essential to mention that, for example, a low entrance fee means, on the one hand, a low economic value but, on the other hand, a high social value since access to the park is facilitated to everyone, regardless of their financial income and therefore favoring everyone's well-being. The same applies to fees charged for workshops or space the park offers.

It must also be mentioned that the size of a park and its density of tree cover positively impact visitors' perception and promote more visits [50]. Larger urban parks receive more visitors than smaller parks, and the size is more important than the distance a park visitor has to travel to go to the park. The fact that larger parks attract more visitors, regardless of distance, could be detrimental to sustainability, given emissions from traffic. Therefore, a minimum green surface area of the park and the surrounding infrastructure, including the park's connection to public transport and bicycle lines, should be regarded [62].

In 2020, Cárcamos Park received an average of 171 visitors per day, considering only the seven months after its opening because of the COVID-19 pandemic. Our methodology does not include the number of visitors per day since the number itself is unimportant. More important is how those visitors get to the park without contaminating the services (recycling center or educational programs) they use, and what they learn from their visit and their behavior inside the park.

Urban parks help to conserve the local biodiversity and can be home to wildlife [63]. Besides the simple distinction between native and exotic plant species, our methodology does not include any distinction of wild animals such as birds, rodents, or amphibians, which could be of interest for the sustainability of urban parks, as mentioned in [64]. The reason for this is that our methodology is applicable to any park worker. This distinction would involve detailed biological research, elaborated on by external experts, since animals move or hide and may be difficult to find or identify, especially insects.

Dizdaroglu [13] considers healthy food as an indicator for sustainable parks. At this stage, our methodology does not include offering, consuming, or promoting healthy food since our focus includes general sustainable data leading to the parks' resilience. However, this aspect might be considered and included in the future.

Dizdaroglu [65] and Dizdaroglu [13] mention the importance of good governance, which includes the consolidation of democratic institutions at all levels to ensure transparency and accountability in governance and inclusive participation in decision-making.

During the case study analysis, potential avenues were identified to be developed and included in the database. In the future, our methodology can be expanded to include additional criteria:

- More transport indicators, i.e., how visitors arrive at the park,
- The human carrying capacity, i.e., how many visitors the park can support to remain balanced.
- Governance indicators, i.e., assess the transparency and accountability in governance and inclusive participation in decision-making.

This article presents a new methodology that is easy to apply by any park manager to parks of any size. The goal is to assign the sustainability grade and show new ecologic, social, and economic areas of park opportunities. This methodology is balanced as it gives equal weight to the three pillars of sustainability: environmental, economic, and social. Its application can identify the strengths and weaknesses of a park's sustainability. The method emerges from a detailed analysis of the park's operations. It incorporates criteria and indicators that have allowed us to assign measurable values and measure sustainability quantitatively. This will facilitate park administrators making the right decisions in the future.

5. Conclusions

In conclusion, our presented methodology represents a valuable and accessible tool for enhancing the sustainability of urban parks. It offers a simple and cost-effective approach to identify improvement opportunities, establish baseline parameters, and guide the allocation of economic resources while justifying their augmentation.

This methodology's significance lies in its ability to bridge the gap between technical complexity and practical application. It employs plain language and basic technical parameters, making it accessible to park managers without requiring expensive consulting services. Users of this methodology benefit from a comprehensive view of park operations, with 19 indicators generated from 50 operational criteria and 18 additional data points. This holistic perspective empowers park managers to assess operational efficiency, make informed decisions, and benchmark their park's performance against others, thereby facilitating the replication of successful practices.

The successful demonstration of this methodology at Cárcamos Park in León, Mexico, resulting in a sustainability score of 57.2%, underscores its practicality. This score falls within the range of average sustainability, between 51% and 79%, and demonstrates its relevance in assessing and enhancing park sustainability. Scores below 51% indicate low or negligible sustainability, while those exceeding 79% signify a high level of sustainability.

In summary, our proposed method represents a dependable tool for evaluating the sustainability status of urban parks. Beyond its immediate applicability, it lays the foundation for further research in sustainable building certification and green area management, including CO_2 capture assessment. Looking forward, we envision automating the database to streamline the assessment process, enabling users to upload information effortlessly and receive automatic results like diagrams and tables for straightforward cross-park comparisons. Additionally, this methodology can serve as a reference for establishing a ranking system for urban parks, fostering collaboration among park managers to refine and enhance its effectiveness continually.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of Cárcamos Park (protocol code DGMA-CE-2023-GTO-002 approved on 30 August 2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

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

Abbreviations

The following abbreviations are used in this manuscript:

E1–E6	Indicators of the environmental pillar
S1–S8	Indicators of the social pillar
EC1–EC5	Indicators of the economic pillar
e+	External dependency with positive impact
e−	External dependency with negative impact
i+	Internal dependency with positive impact
i−	Internal dependency with negative impact
LED	Light-emitting diode
PET	Polyethylene terephthalate
MDPI	Multidisciplinary Digital Publishing Institute
INEGI	National Institute of Statistic and Geography

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Article

Urban Green Development and Resilient Cities: A First Insight into Urban Forest Planning in Italy

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Abstract: The research proposes an application of a modification of the 3–30–300 rule to identify areas that require Urban Forestry implementation in small and medium-sized Roman and/or medieval urban areas. The selected case study is that of Asti in Piedmont, Italy. An open source, cross-platform desktop geographic information system is used to process geospatial datasets via qualitative analyses of electoral sections (or wards). An analysis of the number and distribution of trees around each building is performed, in addition to the calculation of tree canopy cover and distance between buildings and green spaces. Findings reveal that 64 out of 70 wards have an average of at least three trees per building and sufficient green areas of at least 0.5 hectares within 300 m of the buildings. Additionally, the tree canopy cover ranges from approximately 0.6% (lowest) to about 55% (highest) for the electoral sections. Lastly, findings suggest that the highly built-up urban fabric in these areas may significantly affect the availability and quality of green spaces. In conclusion, the case study proves the benefits of applying the 3–30–300 rule to small and medium-sized urban areas using an integrated assessment approach based on nature-based solutions and ecosystem services.

Keywords: nature-based solutions; urban heat islands; InVEST software; urban cooling; QGIS; tree canopy cover; ecosystem services

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1. Introduction

The requirement to reassess the present planning and management of cities and urban settlements from a resilience perspective is an important topic of discussion in mitigation and adaptation policies at an international level, particularly in relation to climate change debates. The United Nations 2030 Agenda for Sustainable Development highlights, in target 11.3, the need to "... enhance inclusive and sustainable urbanisation and capacity for participatory, integrated and sustainable human settlement planning and management in all countries" [1]. Target 11.7 further emphasizes the necessity for "... access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities" (ibid.). Specifically, the 2022 Sustainable Development Goals Progress Report highlights the necessity for policymakers and city officials to "... consider the distribution of open public spaces and green areas throughout the city" as they "... work to redesign and retrofit the spatial configuration of urban areas" [2].

The integration of urban green spaces as public infrastructure providing social and environmental services is becoming crucial in addressing green inequality in urban planning [3]. Since Milton Keynes's Forest City project, several scholars have addressed the development and integration of green infrastructure in both urban and landscape planning. These practices aim to embrace sustainability and resilience [4,5], combining urban forestry planning with the management of urban green spaces [6].

Investigating the abundance, distribution, and types of green spaces is crucial in effectively guiding the design and planning of urban green spaces and forestry to ensure the provision of a range of human benefits [7,8] related to public health [9] through ecosystem services [10]. These effects include the mitigation of ambient air pollutant levels by urban forestry [11] and the provision of food through urban food forestry which combines urban agriculture, urban forestry, and agroforestry [12]. Others, such as Chen and Huang [13], indicated that the demand for green space can greatly vary across neighbourhoods, and areas with a high population density would require more green space. The authors emphasized that future urban greening projects should aim to serve areas with low green space supply, and high demand from people with limited access to green resources.

Defining the quantity and quality of green space accessibility is of paramount importance, as it is often recognised as the difference between spatial heterogeneity and social differentiation [14]. Apart from accessibility aspects, the most advanced and up-to-date techniques used in planning urban green systems often involve using satellite imagery and GIS tools that focus on greenness (e.g., NDVI data) [15].

In decision-making processes on the location of new urban green spaces [16], issues pertaining to equity, justice, and the reduction in socio-spatial inequalities at the city and neighbourhood scale are surprisingly given only marginal consideration.

When focusing on urban forestry (UF), comprehensive assessment of the existing tree canopy is often required for tree-planting programs to support the setting of specific community targets. Remote-sensing technologies such as GIS and satellite imagery, where optical imagery is combined with LiDAR data [17], are often useful for capturing information on the tree canopy. Ideally, tree canopy maps should be accurate to the scale of individual trees, allowing for analysis of the tree canopy at different scales, both at the city level and at the individual plot level [18].

Furthermore, UF planning and management, as well as nature-based solutions (NbS), and especially the topic of UF as NbS [19] are primarily studied in medium- to large-sized urban areas in the United States [20,21]. However, China and Europe are currently exhibiting keen interest in these topics [22,23]. This discourse is also applicable in compact and densifying cities, where "Precision green-space planning for in situ and ex situ densification could . . . prepare redevelopment and new development areas for greenery preservation and installation. Urban forestry could better integrate urban form and density . . ." [24].

Based on the aforementioned concepts, this research aims to present preliminary results that contribute to the planning of urban forestry, to support small and medium-sized administrations. The city of Asti, which constitutes a compact urban centre with a significant Roman and medieval past, located in the northwest of Italy, serves as the case study.

The approach is based on several international recommendations for this purpose. Among the international recommendations, the most pertinent and holistic approach for this purpose is the 3–30–300 rule [25]. One reason behind this statement is that the above rule highlights the advantages of urban forests, a less explored topic in other recommendations or similar rules [26].

Research Aims

This research aims to identify the areas in Asti (Piedmont, Italy), which should be prioritised for UF implementation. To achieve this objective, the study adopted the 3–30–300 rule [25].

However, applying this rule to small and medium-sized historical cities with a compact layout (i.e., Roman planning and/or with a medieval fabric) requires considering the territorial context and the municipal administration's management of the area, especially with reference to Asti as a case study. Therefore, the authors suggest a practical application of the 3–30–300 rule, by dividing the city into electoral sections (or wards) as a functional unit, and evaluating the quality (mainly referring to NDVI values) and the health status of green spaces. This evaluation will guide the prioritisation of areas for UF implementation in Asti.

This paper presents an innovative idea of employing diverse functional units and the fact that the above rule has not yet been applied much in urban realities, especially in the compact small-to-medium sized locales with historical urban layouts of mainly Roman and/or medieval layout. This spatial unit, always referring to the administrative boundaries of the municipality, is commonly present in small and medium-sized European cities, primarily in Italy, where the concept of neighbourhood subdivision is largely absent.

Improving the living conditions of various living beings in urban realities depends not only on the presence or absence of green spaces (especially UF), but also on their quality. Thus, this aspect will also be taken into account during the modification and implementation of the regulation.

The research meets some of the Sustainable Development Goals set by the United Nations including Goal 3 (target 3.9), Goal 11 (targets 11.6, 11a and 11b), Goal 12 (targets 12.2 and 12.8), and Goal 13 (targets 13.1 and 13.2) [1].

2. Materials and Methods

2.1. Study Area

The city of Asti (44.9° N, 8.206944° E) is located in the Piedmont region of northwestern Italy. It covers a total area of 151.31 km^2 with a population of 73,495 inhabitants, giving a population density of 485.72 people/km^2 as of 31 October 2022 [27]. The city has an average green area per inhabitant of 12.64 m^2, which is higher than the minimum value of 9.0 m^2 per person for public areas provided for greenery, play and sport, as laid down in Italian Interministerial Decree no. 1444/1968, point 3.C [28]. Specifically, it counts on an urban tree stock of about 12,500 specimens, of which 4500 are in tree-lined avenues and about 14,000 m of hedges, as of 2016 [29]. The most common species are linden, sycamore, hornbeam, ash, ginkgo biloba and mulberry, including two metasequoias.

As of January 2023, the city of Asti does not seem to be divided into districts, but rather into constituencies and 78 electoral sections (or wards). Therefore, in order to carry out appropriate analyses of the urban fabric of the city, it was decided to use the electoral sections (or wards) and their respective areas (Figure 1). The wards were discarded because in-depth studies cannot be carried out in the most urbanised part of the city.

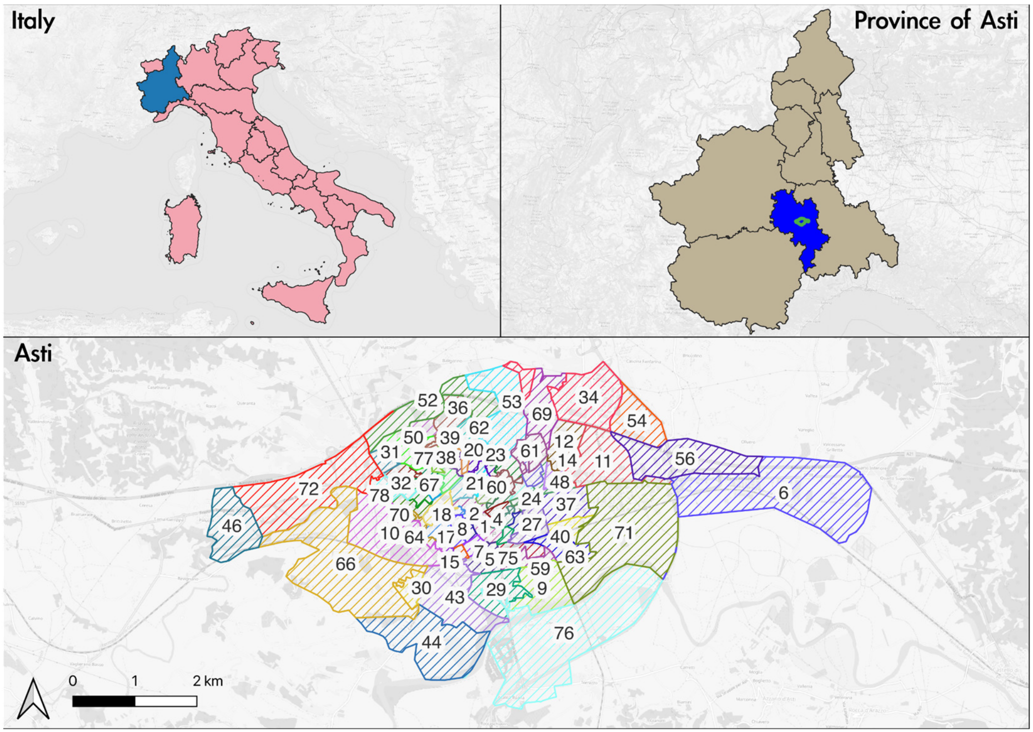

Figure 1. Location of the city of Asti and its division into voting sections or wards. (Sources: Google Maps and OpenStreetMap for the maps; SIT Municipality of Asti for the voting sections. Available online at [30]. Authors' elaboration).

Appendix A provides details of the voting sections in Asti to help understand their areas. This division was found to be the most efficient way to analyse the city in relatively small areas and to accurately identify risk factors and pressures. The use of electoral wards is ideal for small to medium-sized cities, including those with a historic urban layout, where there are no official administrative divisions into neighbourhoods or districts. As for demographics, as of 1 January 2022, the average age of citizens of Asti is 46.2 years, compared to 43.8 years in 2012 [31]. Appendix B displays the different age groups into which citizens can be divided effective from 1 January 2022. As Asti is indexed by ISTAT as the 75th city in the country in terms of population residing in the main city [32], this method has the potential to be replicated in another 7826 Italian municipalities, out of a total of 7901, as per data updated on 1 January 2023 (ibid.).

2.2. Research Methodology

This study proposes a review of the application of the 3–30–300 rule to compact small and medium-sized towns and cities with a strong historical background that feature Roman planning and/or have a medieval fabric. The rule, which actually has a guideline nature, suggests that each resident should have a view of at least three trees from their residence, each neighbourhood should have 30% tree cover and the nearest premium public green space (of at least 0.5 hectares) must be within a 300 m radius.

The next paragraphs will detail all datasets used in this experiment. To encourage replicability of the experiment in other cities, the data refer to publicly available geospatial datasets or those provided directly by the public administration. The analyses were conducted using QGIS 3.x, an open-source, cross-platform desktop geographic information system. All data used are from the year 2018.

Analyses were conducted at both city level and the level of electoral sections (wards). At the qualitative level, findings were classified into five categories: very low, low, medium, high, and very high. This subdivision facilitated a simple and intuitive comprehension of the data, providing a clear framework for comparing and categorising different variables.

One of the key objectives of this approach was to share the final analysis with the public administration and decision makers, such as urban planners or policy makers, and assist them in making data-driven decisions. This was achieved by using descriptive terms such as 'very low', 'low', 'medium', 'high', and 'very high', which make it easier to communicate the results to a wider audience. These featured categories provide a common language that is easily understandable and relatable to by the audience, even if they are unfamiliar with the technical specifics of the analysis. This study aims to highlight how the 3–30–300 rule serves as a useful guideline for policy and planning purposes and stimulates debate about urban greenery and UF. Furthermore, this rule can be applied in various urban cities to analyse the status quo and develop future strategies for increasing or maintaining UF. It is important to note that the primary focus of this study is not to compare results between different cities but instead to analyse differences within the same one with the aim of reducing possible social inequalities [25].

The area analysed does not include the agricultural, wooded, and hilly areas surrounding the built-up zone, as their management is often entrusted to private owners and the remaining public spaces are managed differently in urban areas. This decision was made after the authors conducted three visits to the city in October 2022, and February and June 2023.

2.3. Three Trees per Building

The 3–30–300 rule also includes an analysis of the number of trees in the vicinity of each building. For this purpose, the building data were extracted from the open geographic database OpenStreetMap, while the tree map was collected from the publicly available Territorial Information System (SIT) of the municipality of Asti [30]. In this case, the tree data refer to the census carried out by the municipality or commissioned experts and not to the actual number of trees in public and/or private areas.

Combining the building location with the tree location, we proposed to analyse the presence of trees in a 30 m buffer around each building in the city of Asti. The distribution of tree species at the urban scale was analysed using the buffer function available in the QGIS geoprocessing tools, using the distance of 30 m from each building. Specifically, for each building, we searched for nearby trees by looping through all the trees in the area and calculating the Euclidean distance between each tree and the building location. A tree was considered to be close to the building if the distance was 30 m or less.

For the analysis of the electoral sections or wards, zonal statistics were carried out on a raster file, using as a reference vector the territorial division into electoral wards downloaded from the portal of the Municipality of Asti.

The average was used as a parameter for the analysis of the zonal statistics. The data were divided into five classes, comparing the values of polygons with at least three trees and the number of buildings in the polygon.

2.4. % Tree Canopy Cover in Asti

To calculate the tree canopy cover in the municipality of Asti, the data available in the Pan-European High-Resolution Layers—Forests (2021) were used, in particular the 2018 data on tree cover density at 10 m resolution (ranging from 0–100%). For this data layer, the main sources are (since the 2018 reference year) Sentinel-2 and Sentinel-1 satellite imagery, in which the TCC of tree species in both public and private areas has been considered.

For the urban analysis, the values have been thematised in equal 10% intervals. For the electoral area analysis, the mean values inside the electoral district have been computed and thematised by dividing them into five intervals.

2.5. Distance between Buildings and Parks

The 3–30–300 rule requires an analysis of the distance between buildings and green spaces (within a radius of 300 m) with a minimum size of 0.5–1 ha. This size is derived from studies and recommendations of the World Health Organization [33].

The data for parks and gardens refer to the census of public green areas provided by the municipality. Therefore, the analysis does not take into account both private areas and green areas designated for other uses, such as agriculture.

The data were obtained from the SIT of the Municipality of Asti and then processed at the level of city and electoral sections (wards).

For this purpose, the distance between each building and the nearest mapped green area was computed. The *distance to nearest hub* algorithm, available in the Processing Toolbox in QGIS, was used for the calculation. The algorithm, which takes an origin (i.e., the building) and a destination layer (i.e., green areas), calculates the distance between the origin's features and their closest destinations. The distance calculations were based on the centre of features. Afterward, the average distance was extracted at the level of electoral sections (or wards) using zonal statistics.

2.6. Quality of the Green Spaces in Asti

To assess the quality of the green spaces in Asti, the Normalised Vegetation Vigour Index (nVVI) [34] was computed and analysed by the authors. The authors generated the layer utilising a time series of Normalised Difference Vegetation Indexes (NDVIs), which were calculated from Sentinel-2 satellite images to assess the greenery vigour. This was achieved by analysing the phenology of the area and its relation with trees' growth and health. For every date during the cloud-free periods in 2018, NDVI maps were created using the Sentinel-2 data. The NDVI profiles were regularised applying splines with a time step of five days. Subsequently, they were filtered by FFT with the aim of minimising local fluctuations and emphasising the periodicity of the phenological trend. The Start of Season (SOS) and End of Season (EOS) were calculated at the pixel level using a 2nd derivative approach. The annual NDVI integral was then computed, and divided by the length of the growing season, to obtain an integrated NDVI. An integrated NDVI map was generated for the year 2022 with a Ground Sample Distance (GSD) of 10 m. The average integrated NDVI value for the given tree areas was computed using zonal statistics. The integrated NDVI was normalised to a range [0–1]. It was assumed to be a predictor of tree decline, with a value of 0.5 used as the threshold for distinguishing between potentially declining trees and healthy ones. Finally, the range of [0–1] was divided into five equal intervals.

3. Results

This section presents the results obtained from analyses conducted at the city level and electoral section (or ward) level.

3.1. Three Trees per Building

The findings display the occurrence of tree species within a 30 m radius of each building in the urban area of Asti (Figure 2). The findings have been categorised into five classes (from 'Very Low' to 'Very High') at the electoral section level.

The left-hand map identifies the buildings with colours indicating the classification according to the number of trees within a 30-m buffer. Precisely, the 'High' category represents buildings surrounded by over three trees, the 'Medium' category corresponds exactly to three trees, and the 'Low' class stands for containing fewer than three trees.

On the other hand, the map on the right illustrates the analysis conducted within the voting sections (or wards), using the aforementioned intervals. This classification considers the number of buildings, electoral wards, and their respective average scores.

The study results indicate that 64 out of 70 electoral sections (or wards) had an average of at least three trees per building, demonstrating a high tree density throughout the surveyed areas.

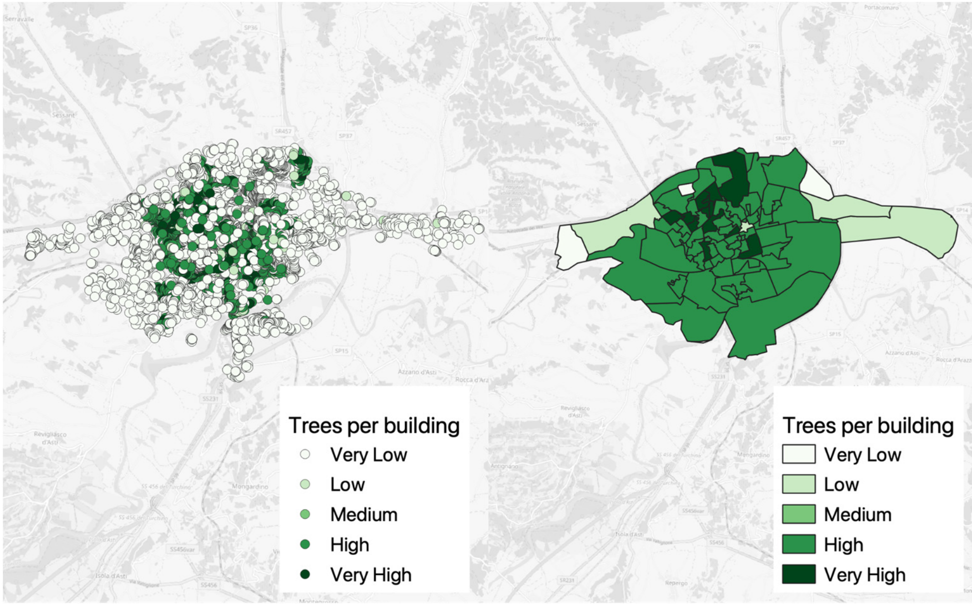

Figure 2. The presence of a minimum of three trees within a 30-m radius of buildings. The left image identifies the buildings, while the right image classifies the electoral sections based on the number of trees surrounding each building. The score inside the voting district is computed by averaging the scores of each building. (Source: OpenStreetMap and the map of trees provided by the Municipality of Asti. Authors' elaboration).

3.2. % Tree Canopy Cover in Asti

Figure 3 shows the percentage of tree canopy cover (TCC) in the city of Asti. The results have been divided into five classes, ranging from 'Very low' (≤10%) to 'Very high' (>40%), based on the electoral wards.

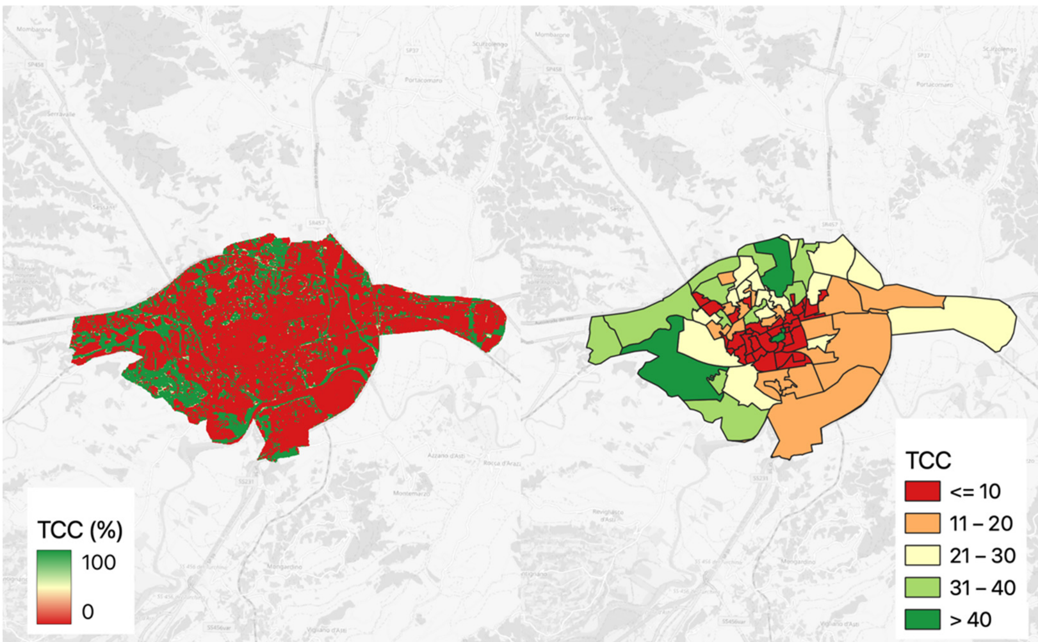

Figure 3. A percentage analysis of tree canopy cover (TCC) at the city and electoral section level. (Source: OpenStreetMap. Authors' elaboration).

Figure 3's left-hand side displays the TCC values for Asti. In contrast, Figure 3's right-hand side analyses the spatial unity of electoral wards and displays the TCC value division into five classes, which comes from a subdivision into equal quantiles. Electoral wards' values range from roughly 0.6% to about 55%.

3.3. Distance between Buildings and Parks

The results concerning the distance of buildings from green areas in Asti are presented below, considering a radius of 300 m and a minimum size of green area of 0.5 ha (Figure 4). The analysis of this parameter was conducted at both the city level and the electoral section (or ward) level. Specifically, the analysis utilised the map of publicly owned green areas provided by the Territorial Information System (SIT) of the Municipality of Asti.

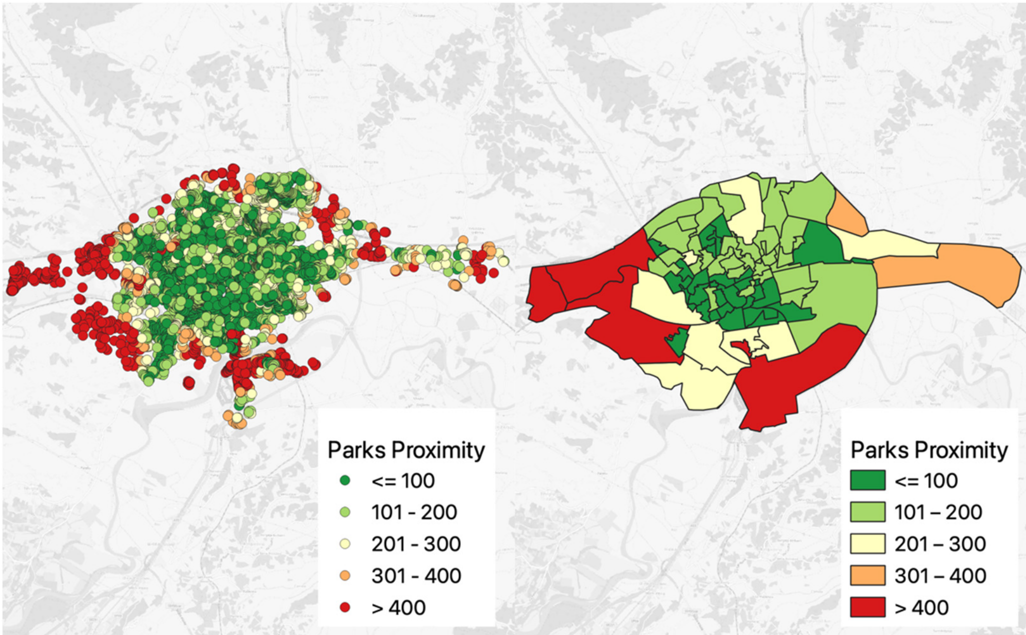

Figure 4. Distance of buildings from green spaces and parks of 0.5 hectares or more. (Source: OpenStreetMap and map of public green areas provided by the Municipality of Asti. Authors' elaboration.).

Figure 4 shows the proximity map results at the city level on its left-hand side. The division into five classes adheres to the following intervals: 'Very Low' (greater than or equal to 400 m); 'Low' (from 300 to 400 m); 'Medium' (between 200–300 m); 'High' (from 100 to 200 m); 'Very High' (less than or equal to 100 m). The classification for the electoral sections (or wards) was the same.

The results indicate that 64 out of 70 electoral wards satisfy the requirement of having at least 0.5 ha of green areas located 300 m away from buildings. However, 56 electoral wards fail to meet the 3–30–300 rule parameter. The primary reason for non-compliance is the requirement of a minimum 30% tree canopy cover. The size of the areas located far from the city centre is a significant factor contributing to the non-compliance with the 30% tree canopy cover rule. The aerial sizes of these regions are larger than those of the central areas, which makes it more challenging to achieve the desired canopy cover. Furthermore, some wards may have an adequate number of trees, but often they do not meet the required canopy-cover value due to their youth and size. Juvenile trees have less canopy cover and require time to grow, thus diminishing their overall contribution to the total canopy cover. Moreover, smaller or elongated trees cover less surface area, further affecting the achievement of the target canopy-cover percentage.

3.4. Quality of the Green Spaces in Asti

Figure 5 below displays the results regarding the quality of green spaces. The results at the urban level were categorised into five classes, ranging from 'Very low' to 'Very high'.

The results indicate a significant variation in green quality among different areas. The study highlights that the areas situated more centrally have a lower to medium-low quality of green spaces.

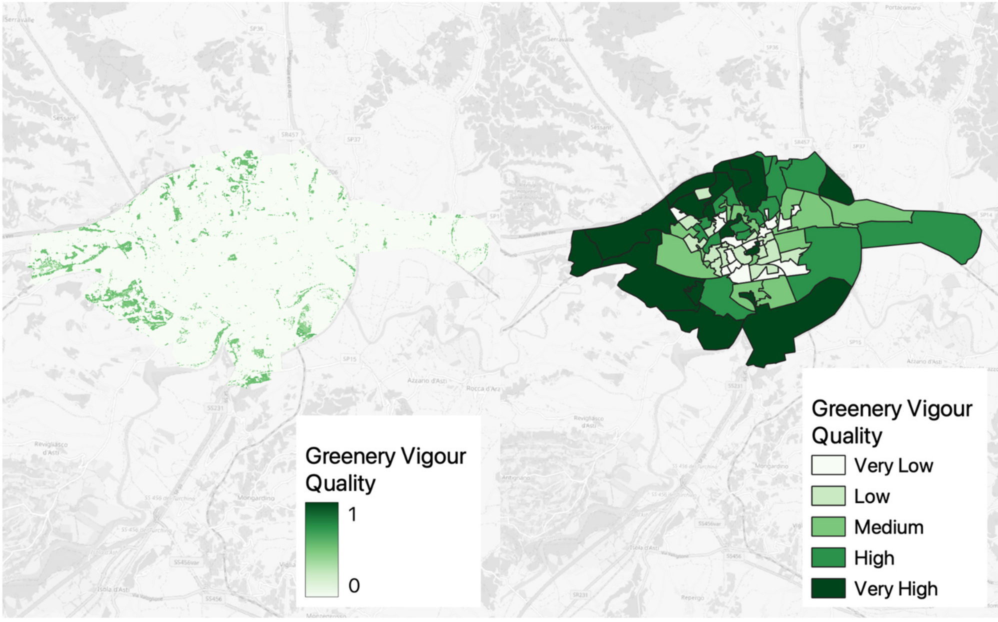

Figure 5. Analysis of the greenery vigour quality at the city and electoral section (or ward) level. (Source: OpenStreetMap. Authors' elaboration).

The findings suggest that the densely populated urban areas may significantly affect the availability and quality of green spaces. On the other hand, the surrounding areas, which may have experienced less intensive urbanisation, show a gradual increase in green quality along the surrounding belt of the densely populated city centre. The observation suggests that these outer regions provide more favourable conditions for the development and maintenance of green spaces, which leads to better green quality. Overall, the results emphasize the importance of urban planning strategies and spatial factors to enhance green quality and promote a healthier urban environment in the city centre.

4. Discussion

4.1. Planning and Management of Green Spaces in Urban Contexts

The planning and management of green spaces in urban areas, with a focus on urban forests (UF), is gaining interest globally, especially in the USA and Canada [35]. This study mainly aims to identify areas where UF can be implemented as Nature-based Solutions (NbS). Implementing NbS requires a prior assessment of the available area suitable for the specific NbS [35]. This study presents a methodology proposed by the authors to implement NbS in medium-sized to small urban settlements, considering green quality. In response to these challenges, the authors propose implementing and adapting the 3–30–300 rule. This rule is based on the smallest spatial unit that a municipal administration can consider in Italy and Europe. Although the IUCN has proposed this rule internationally and it could have a significant impact on policy and governance, there are currently few articles describing its application or potential modifications. This is likely due to the recent proposal of the rule. This approach can also be applied in urban centres where the city centre was built centuries ago and may not have been divided into neighbourhoods. This rule applies in countries which are part of the European Mediterranean area, such as Italy, France, Spain, and Greece, as well as in some Balkan areas, such as Albania.

Potential areas for intervention should be identified and commented upon based on the city's planning and the three field surveys conducted in the city's electoral sections (or wards) in October 2022, and February and June 2023, as shown in Figure 6. This Figure only serves as a tool to initiate discussions. Based on the cross-analysis of the data and field visits, certain areas in the south/southeast of the city of Asti have the potential to host nature-based solutions (NbS). These areas have good connectivity to the existing ecological corridors associated with the Tanaro River, the WWF La Bula Oasis and the Belangero Ponds (44.878822° N, 8.209906° E), as well as to the western region where the Special Nature Reserve of Valle Andona, Valle Botto and Valle Grande (44.9409° N, 8.1151° E) is situated. Aimar et al. (2022) also reported on the significance of the Tanaro riverbank landscape as a heritage asset, with an ongoing process to obtain a Declaration of Public Interest [36], p. 16.

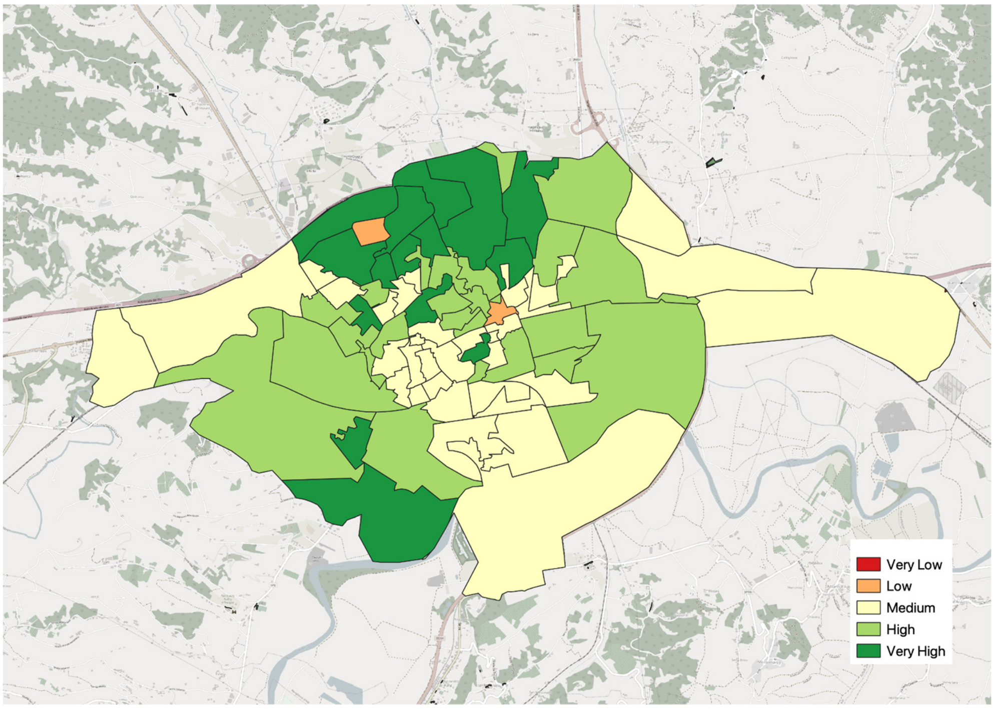

Figure 6. Classification of areas according to potential need for implementing nature-based solutions (NbS). Classes with lower value indicate a greater need for intervention. (Source: OpenStreetMap. Authors' elaboration).

The areas to the east and west of the study location are productive farms that largely cultivate arable crops. To a lesser extent, they grow fruit trees such as hazelnut, walnut, cherry, pear, peach, mulberry, and vines, among others. These fruit plants could also be included in implementing NbS in urban areas as part of the urban food forestry framework. This should consider microclimatic conditions and climate change scenarios. However, it is important to ensure that the fruits of these plants do not affect pedestrian and cycle paths and car traffic or compromise the cleanliness of public spaces.

These theoretical recommendations may assist the administrative and political managers of the Public Works, Urbanism, and Planning and Environment sectors in the Municipality of Asti in developing interdisciplinary strategies and actions to implement and establish new initiatives in different wards. Conducting such a study may aid in complementing the development of an Urban Greening Plan and Greening Regulations, which are currently absent in the municipality of Asti.

Currently, there is only a 2014 Census of Urban Green, last updated at the end of 2015, available from the former Green Office, which is not presently online. Moreover, there exists a potential discrepancy in the categorisation of neighbourhoods between the Green Census which classifies them based on the park grass-cutting contracts, and the Urbanism and Planning Sector of the Municipality of Asti. Currently, third-party organisations appear to be responsible for conducting this census, as the operations of the said office have been discontinued. Since March 2021, representatives of the local administrations and the provincial professional associations (Order of Agronomists and Foresters, Order of Architects, Planners, Landscape Architects and Conservationists, Order of Engineers, College of Agrotechnicians and Graduate Agrotechnicians, and College of Surveyors and Graduate Surveyors) and the third sector (Legambiente, Cittadinanzattiva Asti, Forum Salviamo il Paesaggio, Associazione Terra, Boschi, Gente e Memorie, LIPU Asti, Landscape Observatory for Monferrato and Astigiano, and WWF Asti) have worked together on a draft Urban Greening Plan and Greening Regulations, but these documents were never adopted.

4.2. Comparisons with Other National and International Cases

The 3–30–300 rule indicates that the number of trees and tree canopy cover are crucial indicators to plan new UF spaces in cities. The Senseable City Lab of the Massachusetts Institute of Technology (MIT) is known for its analyses of these parameters. They pay particular attention to measuring the tree canopy cover (TCC) of cities among various tools and studies. The TCC of London (12.7%) has been compared to that of New York (13.5%) and Amsterdam (20.6%) in the MIT study [26]. The city of Turin was analysed in Italy, and its TCC value was found to be 16.2%. However, data on TCC for small and medium-sized cities are currently unavailable. However, Asti TCC, with a value of 25.7%, shows a deviation of 9.5% from Turin, the first Italian capital. The paper's findings demonstrate that the Pan-European High Resolution Layers—Forests data analysis resulted in a tree cover value for Asti. Hence, the utilisation of diverse techniques and resources might produce slightly varying results and, consequently, exhibit divergences in the regions suitable for UF implementation. Different methodologies have been adopted in the debate on the implementation or upscaling of NbS in urban settings. Planting tree species with European case studies is one of the most frequently used techniques, and scenario analysis techniques are vital in this regard [37,38]. Our research is not a replacement for these analysis techniques, but rather a method to be performed in advance or in conjunction with other methodologies.

The initial findings of this study emphasise the quantity of trees surrounding buildings. Nonetheless, there is no evidence of whether they can be seen from the houses nearby. The next step in the research could involve an accurate evaluation of this aspect, as has been attempted in other similar studies [39]. Despite this, it was chosen to utilise the data supplied by the city council. This approach may encourage the collection of green data in areas where they are lacking and also facilitate the comparison of data from different municipal administrations in Europe and Italy. It is important to note that the aim is not to promote a 'Green Olympics' but to initiate a discourse on greenery and analyse the condition of greenery, particularly the UF, to prioritise areas of the city in need of resources and attention.

While the number of trees around buildings in the central part of Asti is discrete, the TCC values tell a different story. This outcome may be attributed to the tree species and their age, considering that only trees planted prior to 2018 were evaluated, making them at least 5–6 years old. It could also be because of the health of the tree species or management activities such as pruning. Studying this aspect would be valuable to create a more accurate connection between the characteristics of different species and the provision of specific ES in Asti. This has already been conducted for Turin according to reference [40].

The study's results on the distance between buildings and green spaces enable comparisons with other cities. For instance, in Sheffield, green areas are less proximate [41]. Conversely, in Berlin and Łódź, there are large green spaces nearby residential areas [42].

Maintaining green quality is critical, especially for tree species that are prone to dying or decaying over time. Furthermore, not all plant species thrive after being planted. According to a 2015 study, around 67% of the trees planted in the Million Trees Los Angeles programme did not survive [43]. An earlier study covering southern Berkeley to western downtown Oakland in California revealed that 34% of trees died within the first two years of being planted [44]. It additionally suggests that trees near housing and public green spaces have a higher mortality rate than those near single-family houses and rapid transit stations [44].

4.3. Further Steps

Some scholars have reported that the enhancement of UF as NbS in urban areas can have advantages for managing air pollutants, notably microparticles (MPs) [45–47].

The 2022 report of the Italian National System for Environmental Protection (SNPA) identifies critical environmental concerns for the city of Asti. The report anticipates that the city will exceed the daily average limit of 50 $\mu g/m^3$ over a significant number of days. Specifically, the two stations located at Baussano Nursery School and Salvo D'Acquisto Primary School are predicted to exceed the limit for 75 and 43 days, respectively [48]. These values should not exceed the limit more than 35 times per year. The annual mean levels of particulate matter with a diameter of 10 μm (PM_{10}) at the stations mentioned are quite high, measuring 37 and 30 $\mu g/m^3$, and they exceed the annual limit of 40 $\mu g/m^3$ [48]. With respect to ozone (O_3), there were 58 days in which the long-term objective for the protection of human health was exceeded, which is higher than the maximum of 25 days [47]. The significance of these levels should be analysed thoroughly, taking into account not only the short term but also the medium term, in relation to the new limit values proposed by the European Commission in Directive 2008/50/EC of the European Parliament and of the Council on ambient air quality and cleaner air for Europe, which will come into effect on 1 January 2030 [49], and the World Health Organization guidelines [33]. A daily limit value of 45 $\mu g/m^3$ is proposed for PM_{10}, which should not be exceeded more than 18 times in a year. Additionally, a threshold value of 20 $\mu g/m^3$ is proposed [33]. Legambiente reports that the average annual variation (%) during 2011–2021 for PM_{10} and nitrogen dioxide NO_2 is only −3% and −5%, respectively [50]. It confirms that in order to comply with the new limit values scheduled to be introduced at the EU level from 2030, a reduction in concentrations (%) of −39% for PM_{10}, −50% for $PM_{2.5}$, and −11% for NO_2 (ibid.) will be necessary. Based on the above data, there is a risk that it may take 130 years to meet the 2030 limit values for PM_{10} and 22 years for NO_2, if the ten-year 'business as usual' trend continues.

To achieve this end, Sofia et al. propose "... the implementation of a strategic plan focused on reducing multi-pollutant emissions" [51], aligned with the call to "... prevent pollution" by identifying "... key urban greening and innovation needs" (ibid.) under "Flagship 2: Supporting urban zero pollution action" [49]. Despite the critical issues identified above and the urgency for action, the current response to mitigation seems insufficient.

In addition, the city experienced the "... occurrence of a good number of dead/felted or decaying trees in two local avenues" (i.e., in Corso Torino and Corso Matteotti) [47], totalling 126 out of 407 specimens (about 31%) in March 2019. Additionally, the urban air-pollution monitoring station present at the Baussano Nursery School is located within an area having a very low tree canopy cover, ranging between 0 and 4.9% (Figure 3). It can be concluded that the current state of urban green infrastructure is inadequate and requires additional measures to include all expected features, before any considerations can be made to improve its quality and quantity with different plant species. Selected tree species such as Curly Maple (*Acer platanoides*), Warty Birch (*Betula pendula*), Turkey Oak (*Quercus cerris*), Ginkgo biloba, Native Lime (*Tilia plathyphyllos*), Bagolaro (*Celtis australis*), Wild Lime (*Tilia cordata*), the Common Elm (*Ulmus minor*), the Common Ash (*Fraxinus excelsior*), and the Black Alder (*Alnus glutinosa*) should be chosen for their higher capacity to stock CO_2 in tons over 20 years (ranging from 3.8 to 2.6 tons depending on the species), as well as their ability to mitigate gaseous pollutants and particulate matter (medium/high/high) [50]. The species mentioned above require evaluation in terms of their susceptibility to climate change impacts and the transmission of plant diseases over time.

It is important to note, within the context of this work, that the authors did not propose a multicriteria framework for implementing Nature-based Solutions. This could be a potential area for future research. The 3–30–300 rule is not easily applicable for benchmarking practices due to its lack of predetermined standards, thresholds, or best practices. Additionally, the application of benchmarking methodologies in small to medium-sized historical cities is challenging due to unique characteristics and spatial constraints inherent in these urban contexts. This study aims to initiate a discussion on integrating green elements in small to medium-sized cities with distinctive historical structures, while also considering the administrative subdivisions that exist in any urban setting. Integrating the concept of green quality into the regulations facilitates identifying areas in need of attention for green space management and determines suitable sites for implementing Urban Forests.

Finally, it may be beneficial to closely examine and differentiate between districts within cities, where differences in environmental conditions, particularly the heat island phenomenon, can be observed. For this purpose, different software tools such as InVEST, ENVI-met, and Space Syntax can determine these differences.

5. Conclusions

The present research suggests implementing the 3–30–300 rule as a tool to identify areas in compact small- and medium-sized towns and cities with a strong historical background (i.e., Roman planning and/or with a medieval fabric) that require Urban Forestry (UF) implementation. The selected case study examines the city of Asti, located in Piedmont, north-west Italy. Geospatial datasets have been used and processed through QGIS, an open-source, cross-platform desktop geographic information system. As there is no formal division into neighbourhoods, the analysis predominantly focusses on qualitative assessments of the electoral sections (or wards), into which the city is divided.

This analysis involves evaluating the quantity and distribution of trees around each building, measuring the canopy cover, and determining the distance between the buildings and nearby green spaces. According to this study's findings, among the 70 analysed electoral sections, 64 have an average of three or more trees per building. Furthermore, these areas have sufficient green spaces, measuring at least 0.5 hectares and located within a distance of 300 m from the buildings. Additionally, the research indicates that the canopy coverage of the electoral sections differs, with the minimum percentage being about 0.6% and the maximum being around 55%. The findings imply that the densely built-up nature of these locations considerably affects the availability and quality of green spaces.

To conclude, this case study presents empirical evidence supporting the effectiveness of implementing the 3–30–300 rule in compact small and medium-sized urban areas with ancient Roman foundations and significant medieval layering. The study adopts an integrated evaluation approach that combines nature-based solutions (NbS) and ecosystem services (ES), emphasising the utility of this approach in tackling urban forestry challenges. In addition, the paper establishes strong connections between various fields, including agronomy, botany, and planning, in order to identify the characteristics and types of nature-based solutions, as well as the significance of ecosystem services in urban environments. The evaluations conducted in this paper may help improve the well-being of citizens in densely populated urban areas to mitigate the impact of climate change and the resulting urban heat island phenomenon.

Regarding the limitations of the research, the study includes a small sample size, which requires further validation through comparison with similar case studies. Validation of this research can be achieved by combining desk studies with on-field surveys and applying the implemented 3–30–300 rule in other small and medium-sized urban contexts in Italy and Mediterranean European countries. This study only employs data derived from remote sensing. There is no use of socio-economic data, such as population estimates. Remote sensing data are derived using mathematical methods reported in the literature, and thus not expected to have any bias. Thus, the current research should be regarded as an alternative interpretation of the 3–30–300 rule. This rule is a guideline, and consequently, does not have any clear-cut methods. Hence, it leaves room for interpretation. These findings have prompted the authors to reflect on the analysed case study, specifically the city of Asti, Italy. Furthermore, it is hoped not only that the census of tree species will be continuously updated, but also that an assessment of the multiple ecosystem services provided by the plant component in the city will be carried out, in a strategic effort to plan for the needs of both humans and more-than-humans [52]. Regardless of the many directions future research might take, it is hoped is that the issue of managing and co-existing with green spaces will always be considered. Finally, these outcomes can be compared with those obtained from other software to determine the significance of urban heat islands and potential solutions at the urban level in public spaces.

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

Appendix A

Detail of voting sections (or wards) in Asti in June 2022. (Source: SIT Municipality of Asti. Available online at: [30]. Authors' elaboration.)

Electoral Section	Surface Area (m^2)
1	173,172.7905
2	106,113.8278
3	69,266.07123
4	83,175.75926
5	51,467.73573
6	186,325.3677
7	86,879.45382
8	67,576.44819
9	211,016.3571
10	65,716.13559
11	70,279.14157
12	154,173.9954
13	111,896.4273

Electoral Section	Surface Area (m^2)
14	384,759.427
15	168,490.783
16	92,216.31884
17	68,154.05567
18	40,696.41063
19	46,387.08633
20	147,231.3275
21	111,585.5106
22	140,285.8581
23	143,565.6543
24	80,648.14497
25	95,982.72049
26	69,356.77439
27	159,038.9795
28	224,425.3824
29	251,188.3634
30	97,095.54189
31	52,699.68516
32	127,177.2527
33	96,274.78926
34	66,734.74936
35	90,071.17516
36	78,986.41284
37	123,897.7824
38	374,943.4971
39	96,142.49654
40	283,200.8122
41	120,117.815
42	44,104.2415
43	136,746.1469
44	63,264.12716
45	768,396.0947
46	841,885.746
47	142,504.1398
48	311,524.9919
49	129,609.8722
50	570,409.4145
51	500,443.0986
52	415,470.1055
53	3,061,512.657
54	875,635.5672

Electoral Section	Surface Area (m^2)
55	1,077,025.346
56	86,141.88673
57	179,793.078
58	1,573,931.915
59	470,033.0075
60	964,919.8903
61	1,298,339.393
62	166,289.9978
63	798,023.6745
64	2,368,353.175
65	708,319.7279
66	2,318,379.611
67	2,634,245.208
68	1,041,495.407
69	9,7345.22789
70	220,488.8961

Appendix B

The demography of the city of Asti with its age groups on 1 January 2022. (Source: ISTAT, resident population on 1 January: By age [32].

Age Groups	Males	Females	Total
0–4	1335 (52.2%)	1223 (47.8%)	**2558** 3.5%
5–9	1589 (50.5%)	1556 (49.5%)	**3145** 4.3%
10–14	1695 (52.3%)	1544 (47.7%)	**3239** 4.4%
15–19	1678 (51.9%)	1556 (48.1%)	**3234** 4.4%
20–24	1912 (53.0%)	1694 (47.0%)	**3606** 4.9%
25–29	1995 (51.8%)	1853 (48.2%)	**3848** 5.2%
30–34	1994 (51.0%)	1913 (49.0%)	**3907** 5.3%
35–39	1949 (49.5%)	1987 (50.5%)	**3936** 5.3%
40–44	2199 (49.4%)	2253 (50.6%)	**4452** 6.0%
45–49	2690 (49.3%)	2771 (50.7%)	**5461** 7.4%
50–54	2885 (48.9%)	3013 (51.1%)	**5898** 8.0%

Age Groups	Males	Females	Total
55–59	2848 (47.6%)	3129 (52.4%)	**5977** 8.1%
60–64	2411 (47.4%)	2675 (52.6%)	**5086** 6.9%
65–69	2271 (46.9%)	2570 (53.1%)	**4841** 6.6%
70–74	2139 (45.3%)	2579 (54.7%)	**4718** 6.4%
75–79	1576 (43.9%)	2014 (56.1%)	**3590** 4.9%
80–84	1301 (41.6%)	1829 (58.4%)	**3130** 4.2%
85–89	691 (36.5%)	1202 (63.5%)	**1893** 2.6%
90–94	275 (28.6%)	688 (71.4%)	**963** 1.3%
95–99	53 (23.3%)	174 (76.7%)	**227** 0.3%
100+	2 (14.3%)	2 (85.7%)	**14** 0.0%
Total	**35,488** (48.1%)	**38,235** (51.9%)	**73,723** 100.0%

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Article

How Does the Residential Complex Regulate Residents' Behaviour? An Empirical Study to Identify Influential Components of Human Territoriality on Social Interaction

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Abstract: Although urbanisation and urban land limitations are prevalent, residential complexes are seldom discussed as a means of compartmentalising social interactions and contributing to residents' social interactions. Due to the spatial orientation of social interactions, semi-public spaces in these buildings are unable to host residents' interactions due to a lack of appropriate arrangements/establishment of tangible and visible objects. The influential components, however, have rarely been identified in residential complexes. To fill this gap, using the theory of human territoriality, the current study explores the influential physical components of human territorialities in semi-public spaces in four residential complexes and investigates whether a significant relationship exists between human territorialities' physical components and social interactions. This study collected data from 264 residents of four residential complexes with different spatial configuration layouts. Pearson correlation and Spearman's rank correlation are used to evaluate linear and monotonic relationships between study variables. The correlation between spatial configurations of physical components and residents' interactions confirms that spatial configurations influence residents' use of semi-public spaces. Social interaction can, therefore, be improved through green space, brightness, accessibility, and furniture in common areas. The findings prove that residential complexes with clustered arrangements have not performed well in creating social interaction due to the lack of defined spaces and territories for people, but multi-core, mixed, and linear complexes that define several open and semi-open spaces have been more successful in the amount of social interaction of residents. This study is one of the first to identify the influential components using the integration of residents' perceptions and spatial configuration.

Keywords: human territoriality; social interaction; semi-public space; green space; spatial configuration; accessibility

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1. Introduction

Due to urban land limitations and rapid urbanisation in developing countries in recent decades, housing support practices have failed, and housing shortages have intensified from five decades ago because of this trend. Housing authorities promoted residential complex construction in the 90s. It supported housing demand for a few years, but the initiative lost its efficiency due to an imbalance between housing supply and demand in Iran. Nevertheless, living in complexes has become increasingly common, especially in Iran's major cities. Like past experiences in other cities, a problem associated with life in complexes is the poor quality of social interactions [1,2], which deprives an individual of well-being [3] and results in depression, stress, and distress [4]. At the same time, the superiority of economic and population considerations over other human needs reduces the quality of such residential areas [5]. A housing project, particularly a residential complex, should be able to provide security, health, and stability, as well as meet the initial needs of all ages and social groups, thereby satisfying their initial needs, such as comfort, privacy, peace, and dignity [6]. Hence, private and semi-private territories, as a part of privacy, should also be clearly and accurately defined in designing residential areas to avoid unwanted societal conflicts between residents' and users' space [5].

There are three types of territorial spaces based on privacy levels: primary, secondary, and public territory [7]. Madanipour [8] describes territorial behaviour as marking, controlling, and defending. Territorial behaviour is perceived as a mechanism based on enhancing human–environment interactions for regulating social interaction and ensuring stability in social organisations [9–12]. Through signage and personalising a place, users express nonverbal communication to communicate ownership and occupancy of areas and possessions [13]. However, based on the literature, several components contribute to territoriality, including (1) social [14–16], (2) cultural [14,17], (3) psychological–cognitive [14], (4) physical [14,17–22], (5) functional [14], (6) environmental [14,17], (7) temporal–spatial [14,23], (8) economic [14], and (9) individual [23,24] components.

Research has revealed that creating territoriality can improve users' sense of identity, privacy, and security [25]. In addition, territoriality regulates users' routine activities in spaces where routine activities also influence guardianship patterns and monitoring of their surroundings [26]. As a result, creating different spaces to respond to residents' needs must be accomplished by changing users' routine activities, improving welfare, and increasing social interactions [26,27]. Shared and semi-public areas in housing complexes should be designed to reinforce community encounters [26,28] and strengthen bonds between neighbours [29]. A large body of literature demonstrates how the place affects users' interaction patterns in the space and users' satisfaction [10,29–37].

In metropolises in Iran and many other countries, users' territoriality in residential complexes is not currently preserved according to residential block geometrical shapes [35]. Adhering to building codes and building layout regulations resulted in independent parking lots, standard-dimension stairs, and appropriate fire extinguishing facilities in the latest generation of complexes, but semi-public areas decorated with green space emerged without hierarchy [37]. These were created to be a place for users' interactions, engagement, and social network development. However, the current levels of residents' interactions reveal that the spaces failed to fulfil their mission in many residential complexes. It is, therefore, rare to find places where residents can gather to encourage fun and interaction. As a result, residential complexes and housing projects become a series of volumes with vacant shared spaces among them. In general, communication is an initial human need because engaging with neighbours can enhance community inclusion and a sense of belonging, especially in complexes in Iranian cities. A literature review indicates that users' territoriality improves their engagements [30,34,35]. Due to the lack of territoriality in many residential complexes, neighbours cannot look out for their well-being and communicate together to improve living conditions and situations, particularly between different age groups and social classes. Subsequently, a trend of social exclusion has emerged, which grows in centres with high-density buildings and crowded populations, unlike past patterns in Iran [35].

Taking into account the layouts of residential blocks, this study concentrates on the impact of human territoriality in the semi-public spaces of four residential complexes. Despite various studies that have pointed out residents' behaviours, building configuration, connectivity, infrastructure, and quality of place at neighbourhood levels, mass buildings, or both, few studies have paid much attention to the impact of residents' informal territoriality on residents' behaviours in semi-public spaces of mass residential complexes. Accordingly, the present study investigates whether a significant relationship exists between the physical components of human territoriality and social interactions. Second, it identifies the most influential physical components of territoriality on residents' interactions. In the following, as a third point, the authors will illustrate the proposed design for influential physical elements of territoriality in residential complexes according to the research findings. The present study consists of four subsequent sections: the Section 2 reviews the literature on territoriality and social interaction. The Section 3 reveals the methods and instruments employed to satisfy the research objectives and introduces the case study. The Section 4 focuses on analysis and results. The Section 5 elaborates on the findings and concludes research findings beyond case studies. Future research recommendations will be highlighted in this section.

2. Literature Review

2.1. Social Interactions in Built Environments

Three types of activities occur in the outdoors: necessary, optional, and sociable [38]. Social interaction is the result of people in the same spaces and positive interpersonal interactions [35]. Many recent environmental psychology studies focus on the interactions between the built environment and social factors. The physical aspect of a built environment facilitates interpersonal communications and provides privacy in a non-private space. It entails the establishment of appropriate dimensions, spatial arrangement, and permeability in the built environment. Finally, the human-made environment grants symbolic and aesthetic perceptions, experiences, and feelings, which affect users' perceptions of place qualities [39,40]. Desired privacy and spatial relations are created through appropriate spatial arrangement and the establishment of required physical elements in a place [17,41].

In this regard, neighbourliness consists of two aspects: manifest and latent. Although communicating and chit-chatting are two common types of manifest neighbourliness, mutuality and trust among neighbours are consequences of latent neighbourliness [35,42,43]. Hence, Table 1 categorises the physical elements of the built environment influencing social interactions revealed in past studies. According to the findings, most scholars have identified components, such as furniture, light and brightness, accessibility, and green space.

Table 1. Physical factors influencing social interactions.

Researcher	Physical Factors
[44–50]	Furniture
[45,47,51,52]	Pedestrian, path, network
[44–48]	Light and brightness
[35,40,44,49,50,53–60]	Accessibility
[61,62]	Size of space (human scale)
[55,61,62]	Placing and arranging of activities and equipment (floor, body, landscape components in space)
[61,62]	Visual comfort (harmony of the facade in terms of form, colour, materials, skyline, and desired space brightness)
[55,56,63]	Space arrangement and organisation
[30,37]	Readability of public spaces
[54]	Diversity (mixed land uses)
[53,64]	Confinement
[53,64]	Desired landscape

Table 1. *Cont.*

Researcher	Physical Factors
[47,61,62]	Feeling of peace
[50,56]	Parking
[40,65]	Place identity
[47,56]	Visual pleasure
[54–58]	Visual and spatial proportions
[65,66]	Symbolic mechanisms
[26,66]	Boundaries and hierarchies defined from private to public areas
[47,63]	Urban fabric
[47,54,63]	Readability in form and function
[45,47]	Safety
[67]	Components of contemplation and pause
[67]	Informative art, architectural, and advertising signs
[48,56]	Facilities for people with disabilities
[48–50,57,58,68]	Green space and vegetation
[48,50,57]	Sculptures and fountains
[49,68]	Shades
[50,65]	Floor covers

2.2. Territoriality and Social Interactions in Residential Complexes

Residences create a territory that matches the house's legal boundaries [5]. Spatial territoriality is formed based on permeability and accessibility [30,37]. Hence, segmenting of an area results in a better perception of territorialities [69]. Physical territoriality control involves using signs and marks to claim and protect the area. Generally, each type of activity requires certain physical settings to facilitate their occurrence in space, such as playing with others, greeting others, and talking [70]. Passive communication is a social activity, such as eye contact, watching events, and listening to others. Common areas between houses in neighbourhoods facilitate residents' attendance and contribution to various activities [69].

Territories in a residential building include the arrangement of courtyards, towers, landscaping, and flooring of different areas, such as pedestrian and riding paths, along with the arrangement of sites for multipurpose activities, such as playgrounds, sports, retail, and car parking [71]. Currently, residential complexes, which have the potential for semi-private and semi-public spaces, can play the role of local mediators (in-between spaces) to improve social interaction [30,72–74]. Users perceive defined semi-public spaces as having a significant positive effect on social interactions compared with undefined semi-public spaces [75,76]. If different levels of territory are not defined well, individuals will have to fight the environment to achieve appropriate levels of territoriality to enhance social interaction [77]. In a residential complex, residents prefer spaces that provide interaction opportunities [78], along with privacy, which is necessary [35,79]. This concept indicates the importance of territoriality in improving social interactions in living places [80]. Furthermore, previous research findings have demonstrated that opportunities for community activities and the strengthening of the social bond of residents will be increased by preparing green space in residential environments [30,37,81] or an atrium in cold climate areas [82].

Huang [83] believed that water features with complex and distinct forms encourage observers' social interactions. Configuring a proper public facility enhances informal communication and chitchat [30,65,75,84,85]. For instance, Huang [29] found that the concave seating arrangement near plants, closeness to the activity zone, and features of water or works of art can be among the factors that provide users with facilities, such as shade, events, and aesthetic quality, and can encourage interpersonal interaction.

According to theoretical discussion, territoriality and the segmentation of areas are two components of residential complexes that provide better insight into different territories and their control. Reynald and Moir [86] revealed the significance of the physical and social aspects of environments in both providing and promoting opportunities for monitoring and controlling the surroundings by residents. Territories aim to satisfy the various needs of several age groups, resulting in more confidence and privacy for residents and enhancing social interactions between residents. Studies have shown that the development of green spaces through appropriate patterns, the establishment of interesting facilities and activities, and appropriate outdoor furniture arrangements enhance interaction between residents. In this regard, landscape components in open public spaces encourage informal contact and interaction.

2.3. Conceptual Framework

According to the theory of human territoriality, human behaviour depends on providing appropriate spaces for its activities [87], which have a sufficient level of effect, influence, or control over access, actions, and interactions [88]. Thus, behaviours are influenced by different interactive multilevel factors from individual to public policy levels [89]. As a result, a significant relationship occurs among users and their interactions and social–environmental components [90]. As mentioned, a large body of literature revealed that residents' interaction in neighbourhood areas is affected by some physical elements, including the quality of the neighbourhood, housing layouts, communal facilities, seating area and seat arrangements, open space and green area, lighting, accessibility, and pathways [10,30,35,43,91]. In this respect, the physical aspect of the built environment contributes to the creation of territoriality at the level of users, where users act according to their self-perceived territoriality in a public space, such as a neighbourhood or semi-public residential complex [92]. Territoriality, therefore, results from the combination of individual attitudes and physical characteristics of the built environment, which develop social behaviour, such as social interaction [93].

The research framework was designed based on the theory of human territoriality. It involves understanding and applying the principles and concepts associated with territorial behaviour in humans. Hence, Figure 1 shows the proposed conceptual framework, in which individual behaviours are affected by perceived territoriality and built environment components. Through this approach, users' interactions in semi-public spaces of complexes are modified directly and indirectly by the built environment.

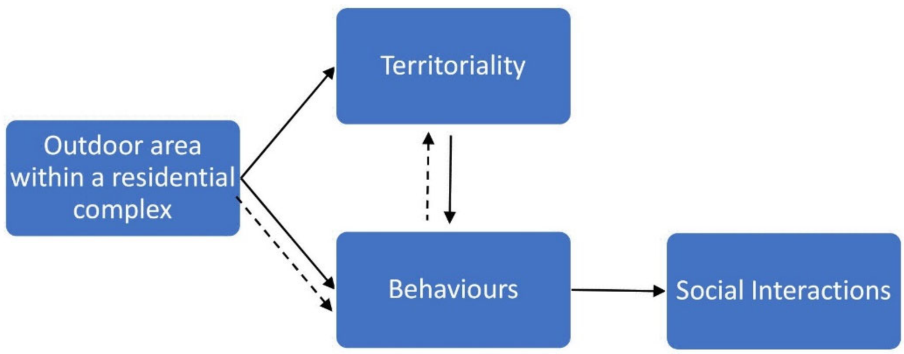


Figure 1. Research conceptual framework.

3. Methodology

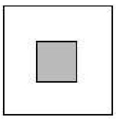
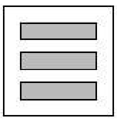
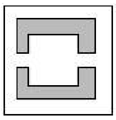
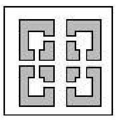
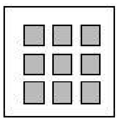
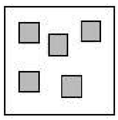
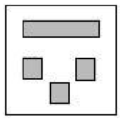
This study employed a mixed-methods approach to satisfy the research objectives, including (A) a closed-ended questionnaire to assess users' characteristics and the experience and perception of interaction with neighbours within residential complexes and (B) the physical characteristics of residential complexes objectively observed by the authors. This study used quantitative analysis methods, such as correlational and descriptive methods, to analyse the collected data. It is a descriptive correlational study that examines the relationship between research variables. Using SPSS 24, the study evaluated monotonic and linear relationships between study variables by Pearson correlation and Spearman's rank correlation.

3.1. Study Area

Four residential complexes in Shiraz, one of the four largest cities in southwest Iran, were selected for the study. The city has a population of more than 2 million people across 152 neighbourhoods and 11 districts, based on available data from Shiraz Municipality. Due to its proximity to less developed provinces, many migrations have made Shiraz a metropolitan city with a heterogeneous population. Hence, privacy, safety, and territoriality are among the main concerns of residents, for whom the potential risk of crime is high [94]. Considering the rapid urbanisation and high demand for housing, irregular and uncontrolled construction has led to housing issues becoming a crisis.

These four case studies were selected based on the following inclusion and exclusion criteria: (1) the spatial configuration unit must be included as one of four types of residential housing complex typology in Shiraz, and (2) the residential complex must have open semi-public space, including sports facilities, playgrounds, seating areas, and landscapes in open space. Furthermore, we excluded employer-provided housing complexes. For this reason, as shown in Table 2, spatial building block layouts in residential complexes of Shiraz have been studied recently. They were categorised into five patterns: (1) individual, (2) linear, (3) centralised (single and multicore), (4) clustered (regular and irregular), and (5) mixed [95].

Table 2. Typology of residential complexes in Shiraz, source: [95].

Pattern	Individual	Linear	Centralised		Clustered		Mixed
			Single	Multi-Core	Regular	Irregular	
Building Block Layout							

Referring to the different patterns, residential complexes were selected in terms of the four patterns from the five typologies listed in Table 2. In this regard, the current study drew site plans of selected residential complexes with a focus on the location of the block(s), unused spaces, green space, and main entrance, as shown in Table 3.

Table 3. Description the case studies, source: authors.

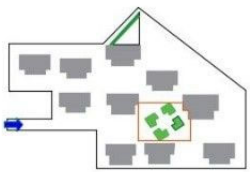
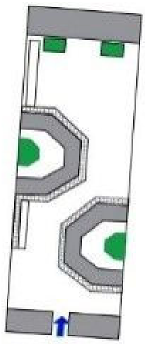
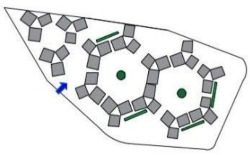
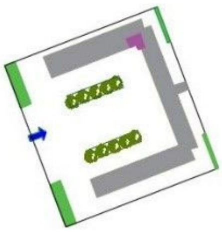
Typology	The Complex Name	Plan	Images
Clustered arrangement	Nastaran Complex		 

Table 3. *Cont.*

Typology	The Complex Name	Plan	Images
Features: This complex is comprised of seven 5-story blocks with three dwelling units on each story.			
mixed arrangement	Jannat Complex		
Features: This complex is comprised of 23 blocks including seven 3-story blocks and sixteen 4-story blocks. Four blocks have 3 dwelling units on each floor, three blocks have 5 dwelling units on each floor, and sixteen blocks have 4 dwelling units on each floor.			
Centralised arrangement	Tose'e-va-Omran Complex		
Features: This complex is comprised of fifteen 4-story blocks, with 268 one-bedroom, 258 two-bedroom, and 74 three-bedroom dwelling units.			
Linear arrangement	Mohandesin Complex		
Features: This complex is comprised of eight 10-story blocks with two dwelling units on each floor.			

3.2. Observation

Although previous studies [29,30,35] investigated social interactions at the neighbourhood level, this study focuses on residential complexes and semi-public spaces within the blocks. Hence, a field observation was conducted to observe and record the physical characteristics and spatial layout of building blocks in the selected complexes. In this regard, the current study investigated site plans of selected residential complexes, focusing on the location of the block(s), forms of semi-public areas, green spaces, light and brightness, accessibility, and shared facilities (as shown in Table 4).

Table 4. Availability of physical components in selected residential complexes.

Component	Index	Nastaran Complex	Mohandesin Complex	Jannat Complex	Se'e-va-Omran Complex
Typology		**clustered**	**linear**	**mixed**	**centralised**
Placing and arranging	Diversity of spaces specific to different age groups	-	-	-	-
	Distance from playground and residential area	-	-	-	-
	Separation of spaces	-	✓	✓	-
	Allocation of parking lots	-	✓	-	-
Green space	Diverse green space	-	-	-	✓
	Separating spaces with green spaces	-	-	-	-
Light and brightness	Effect of light on the readability of turning points and pathways	-	✓	-	-
	Quality of light at night	-	✓	-	-
Accessibility	Separating pedestrian and vehicles	-	✓	-	-
	Hierarchical access	-	✓	✓	-
	Using turning points, intersection, and main pathways for important spaces	-	✓	-	-
	Appropriate access from different areas to public spaces	-	✓	-	-
Furniture	Group furniture	✓	-	✓	-
	Table tennis facilities	-	✓	✓	-
	Playground equipment	-	-	-	✓
	Sport facilities	-	-	-	✓
	Signs	✓	-	-	-
	Sculptures and fountain	✓	✓	✓	✓

3.3. Questionnaire

In the quantitative part, the study prompts residents of residential complexes to fill out a self-administered questionnaire. Hence, a walk-in questionnaire survey was conducted in November 2020. Regarding the available residential population data in the Shiraz Municipality, the total resident population for these complexes is 3174 people (as of October 2020). The stratified sampling method was applied for this study. Of 500 residents who received the questionnaire at their self-units' doors, 303 returned the questionnaire, with a response rate of 60.6%. For most of the other 197 residents, the reason for not contributing to the survey was lack of time. The main inclusion criterion was that respondents had lived on the current property for at least one year. After data cleaning, 39 respondents' questionnaires were excluded due to incomplete and/or inadequate responses or not meeting the inclusion criteria. Therefore, the total number of respondents was reduced to 264. Participants were asked to provide demographic characteristics in the first section of the questionnaire. They were also invited to respond to 23 statements that reflect their experiences regarding the availability of shared amenities, green spaces, lighting and daylighting, accessibility, and social interactions in semi-public areas in their complexes. Table 5 shows the study variables with their respective indicators.

Table 5. Study variables with respective indicators.

Construct	Item	Description
Placing and arranging activities—Items were adapted based on the work of [55,61,62]. (1 = strongly disagree, 5 = strongly agree)		
	Q1	Furniture around facilities and activities
	Q2	Talking in cozy and comfortable corners
	Q3	Walking in pathways through a green space
	Q4	The placement of communal spaces in the focal points
	Q5	Placing the playgrounds in a full natural surveillance
	Q6	Using different forms for collective spaces motivate me
Green spaces—Items were adapted based on the work of [48–50,57,58,68]. (1 = very rarely/little, 5 = very frequently/ very much)		
	Q7	Using the green space of the complex
	Q8	Monitoring green spaces from the dwelling unit or block
	Q9	Reading books and newspapers, playing music and movies in green spaces
	Q10	Extending your attendance due to creative green spaces
Lighting and daylighting—Items were adapted based on the work of [45–48]. (1 = strongly disagree, 5 = strongly agree)		
	Q11	The quality of lighting and your fear of crime in complex
	Q12	Proper lighting extending my public spaces use
	Q13	Proper lighting increases residents' safety and security in public spaces use
	Q14	Proper lighting extends the visibility of activities and open spaces
Accessibility—Items were adapted based on the work of [40,49,50,54–58]. (1 = strongly disagree, 5 = strongly agree)		
	Q15	Proper access motivates me to attend to the communal space
	Q16	Communal spaces with high accessibility motivated users to attend.
	Q17	A full separation of pedestrians and vehicles
	Q18	A high effect between the placement of communal spaces, accessibility, user attendance
Shared furniture—Items were adapted based on the work of [45–50]. (1 = very rarely/little, 5 = very frequently/ very much)		
	Q19	Sufficient outdoor chairs and furniture
	Q20	Using sign boards helps visitors find way easier
	Q21	The quality of sports equipment and furniture boosts residents' attendance and activities
	Q22	Using the proper sculptures and memorials enhance my motivation to attend to space
	Q23	The existence of a proper gazebo, shed, or pergola encourages residents to talk together

In total, 264 respondents participated in the survey, and 51.13% and 48.86% of respondents were male and female, respectively. Additionally, the percentage of respondents by complex residential pattern includes 8% of the residential complex of the linear pattern, 13% of the residential complex of the clustered pattern, 25% of the residential complex of the mixed pattern, and 54% of the residential complex of the centralised pattern. The respondents' residence length includes 2% over 15 years old, 8% between 10 and 15 years old, 35% between 5 and 10 years old, and 55% under 5 years old.

4. Results

This study was conducted based on the environmental meaning model to explain the role of physical components of territory and social interactions in the presence of social groups of residents and to analyse the effective components. The collected data through questionnaires were analysed through SPSS 24 using the Pearson correlation coefficient to illustrate potential relationships between two normally distributed quantitative variables. In this regard, an index coefficient between 1.0 and 1.0 indicates ideal positive and negative relationships, respectively. A two-tailed significance level of 5% was applied to determine if any difference exists between the components we are comparing. Consequently, the analysis of the questionnaire yielded the results detailed below.

4.1. Placing and Arranging Activities

The components mentioned in the first part, related to placing and arranging the activities in residential complexes, are positively and significantly correlated (Figure 2). As a result, the layout patterns of activities and functions in semi-public areas have a positive effect on each other. An alpha value of less than 0.05 confirms this finding (Table 6). Consequently, the use of concave furniture around the playground or the fountains encourages social interaction among residents. The application of quiet and shaded corners, linear passages beside green spaces, the construction of playgrounds and sports fields in central areas of the courtyard, and the use of different forms (e.g., children's parks, space for elderly individuals), as public spaces, result in more effective user relationships. Notably, although allocating a specific space to children or the elderly is a constructive and effective act, statistics show that it does not have such effects on social interactions. This is because the components have no significant correlation.

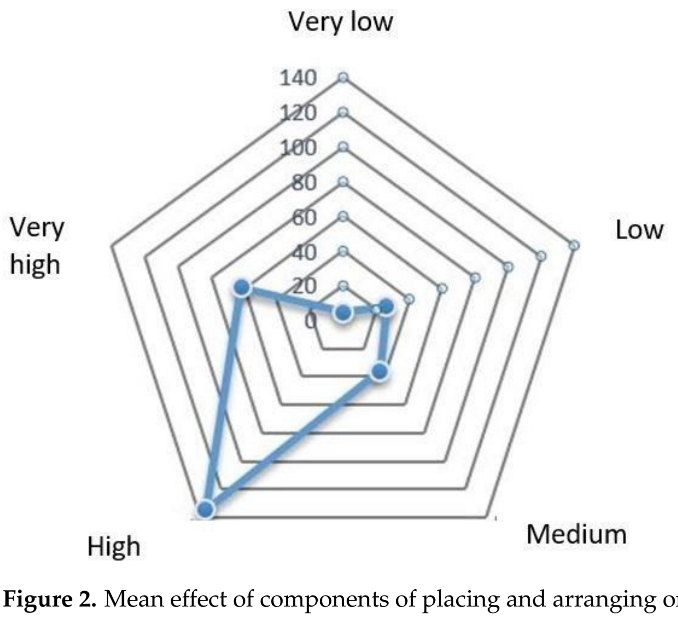


Figure 2. Mean effect of components of placing and arranging on social interactions.

Table 6. Correlation for the placing and arranging components.

		Components of Item 1	Components of Item 2	Components of Item 3	Components of Item 4	Components of Item 5	Components of Item 6
Components of Item 1	Pearson correlation	1	0.283	0.197	0.175	0.202	0.213
	Sig. (2-tailed)		0.000	0.001	0.004	0.001	0.000
Components of Item 2	Pearson correlation	0.283	1	0.339	0.240	0.202	0.070
	Sig. (2-tailed)	0.000		0.000	0.000	0.001	0.256
Components of Item 3	Pearson correlation	0.197	0.339	1	0.259	0.212	0.052
	Sig. (2-tailed)	0.001	0.000		0.000	0.001	0.403
Components of Item 4	Pearson correlation	0.175	0.240	0.259	1	0.299	0.038
	Sig. (2-tailed)	0.004	0.000	0.000		0.000	0.539
Components of Item 5	Pearson correlation	0.202	0.202	0.212	0.299	1	0.221
	Sig. (2-tailed)	0.001	0.001	0.001	0.000		0.000
Components of Item 6	Pearson correlation	0.213	0.070	0.052	0.038	0.221	1
	Sig. (2-tailed)	0.000	0.256	0.403	0.539	0.000	

4.2. Green Space

According to respondents' responses, all components of green space were significantly and positively correlated. As a result, their implementation has a positive effect on each other, which is confirmed by the estimated Cronbach's alpha < 0.05. Only components in Items 8 and 10 are not significantly correlated and do not affect each other (Table 7). Considering the statistical analysis, the components of green space improve social interaction (Figure 3).

Table 7. Correlation for green space components concerning social interaction.

		Components of Item 7	Components of Item 8	Components of Item 9	Components of Item 10
Components of Item 7	Pearson correlation	1	0.176	0.975	0.207
	Sig. (2-tailed)		0.004	0.000	0.001
Components of Item 8	Pearson correlation	0.176	1	0.167	0.070
	Sig. (2-tailed)	0.004		0.007	0.260
Components of Item 9	Pearson correlation	0.975	0.167	1	0.212
	Sig. (2-tailed)	0.000	0.007		0.001
Components of Item 10	Pearson correlation	0.207	0.070	0.212	1
	Sig. (2-tailed)	0.001	0.260	0.001	

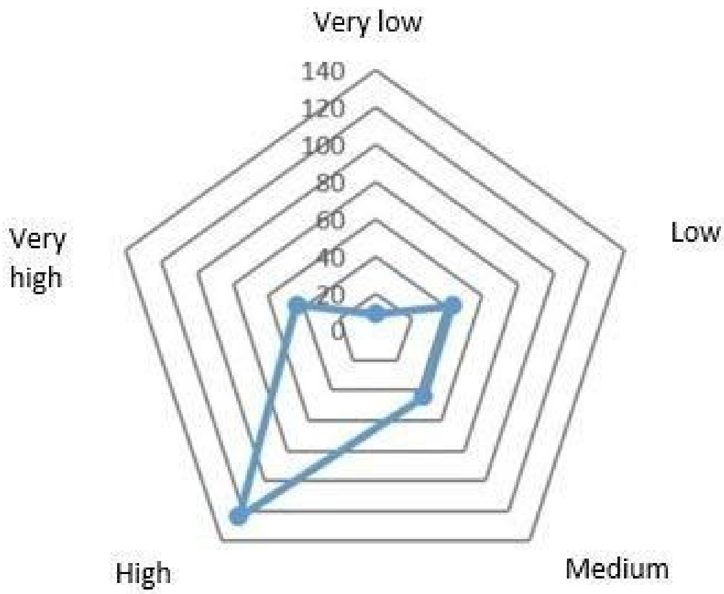


Figure 3. Mean effect of green space components on social interactions.

4.3. Light and Brightness

According to the statistical analysis, spatial light quality had no significant relationships with the other components of items (Table 8 and Figure 4). Other components, such as environmental aesthetic improvement, proper lighting for safety, and legibility of turning points and signs, also affect social interactions and community relationships. An increased level of each component enhances other components and improves social interactions. For instance, augmenting space beauty through light leads to a heightened sense of security, which, in turn, boosts social interaction.

Table 8. Correlation of light and brightness components concerning social interaction.

		Components of Item 11	Components of Item 12	Components of Item 13	Components of Item 14
Components of Item 11	Pearson correlation	1	0.067	−0.075	0.038
	Sig. (2-tailed)		0.276	0.227	0.538
Components of Item 12	Pearson correlation	0.067	1	0.345	0.245
	Sig. (2-tailed)	0.276		0.000	0.000
Components of Item 13	Pearson correlation	−0.075	0.345	1	0.233
	Sig. (2-tailed)	0.227	0.000		0.000
Components of Item 14	Pearson correlation	0.038	0.245	0.233	1
	Sig. (2-tailed)	0.535	0.000	0.000	

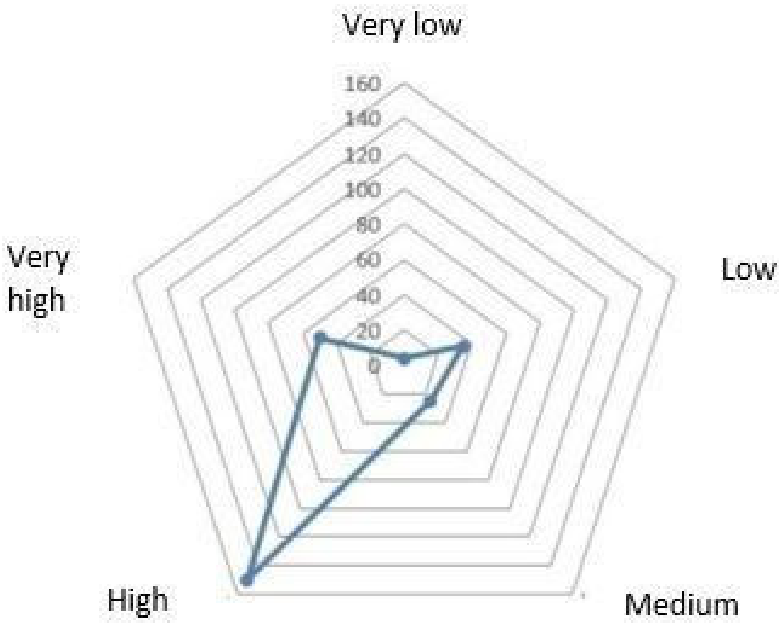


Figure 4. Mean effect of light and brightness components on social interactions.

4.4. Accessibility

The analysis shows a significant relationship between the components (Table 9 and Figure 5), but no significant relationship exists between the separation of pedestrian and riding paths and the hierarchical component of accessibility to public space or between the location of public space and appropriate access to different sites (Table 9). Therefore, these components do not affect each other. Pushing aside, decreasing and/or increasing the level of each component did not affect their effectiveness. These factors are independent and have unique effects.

Table 9. Correlation for accessibility components concerning social interaction.

		Components of Item 15	Components of Item 16	Components of Item 17	Components of Item 18
Components of Item 15	Pearson correlation	1	0.010	0.314	0.278
	Sig. (2-tailed)		0.873	0.000	0.000
Components of Item 16	Pearson correlation	0.010	1	0.158	−0.010
	Sig. (2-tailed)	0.873		0.010	0.866
Components of Item 17	Pearson correlation	0.314	0.158	1	0.543
	Sig. (2-tailed)	0.000	0.010		0.000
Components of Item 18	Pearson correlation	0.278	−0.010	0.543	1
	Sig. (2-tailed)	0.000	0.866	0.000	

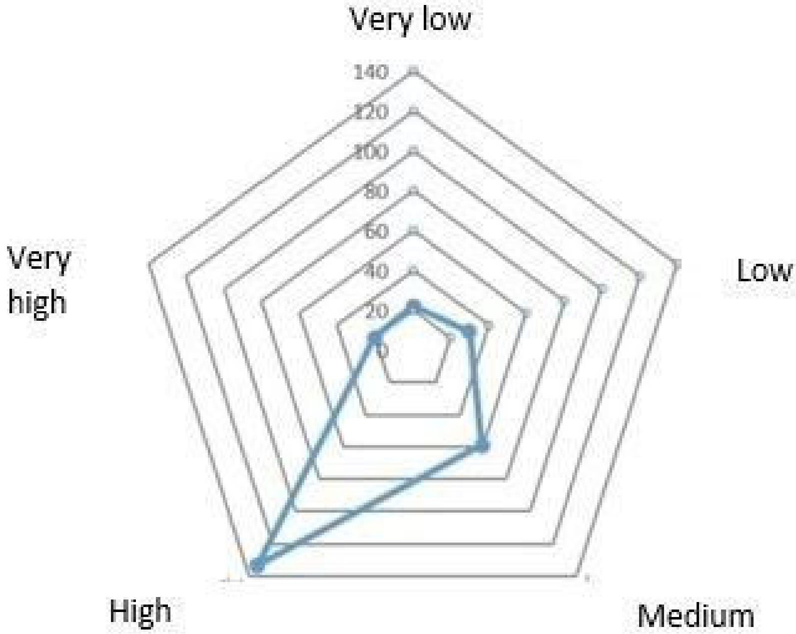


Figure 5. Mean effect of accessibility on social interactions.

4.5. Furniture

Table 10 shows all components are significantly correlated, except for furniture, which has no impact on other components. Figure 6 also indicates signs, tables, and memorial sculptures significantly affected social interactions. Moreover, an increase in each component strengthens other components, which, in turn, enhance social interactions.

Table 10. Correlation for furniture components concerning social interaction.

		Components of Item 19	Components of Item 20	Components of Item 21	Components of Item 22	Components of Item 23
Components of Item 19	Pearson correlation	1	−0.086	−0.030	−0.070	0.045
	Sig. (2-tailed)		0.164	0.631	0.256	0.468
Components of Item 20	Pearson correlation	−0.086	1	0.464	0.246	0.122
	Sig. (2-tailed)	0.164		0.000	0.000	0.047
Components of Item 21	Pearson correlation	−0.030	0.464	1	0.264	0.361
	Sig. (2-tailed)	0.631	0.000		0.000	0.000
Components of Item 22	Pearson correlation	−0.070	0.246	0.246	1	0.183
	Sig. (2-tailed)	0.256	0.000	0.000		0.003
Components of Item 23	Pearson correlation	0.045	0.122	0.361	0.183	1
	Sig. (2-tailed)	0.468	0.047	0.000	0.003	

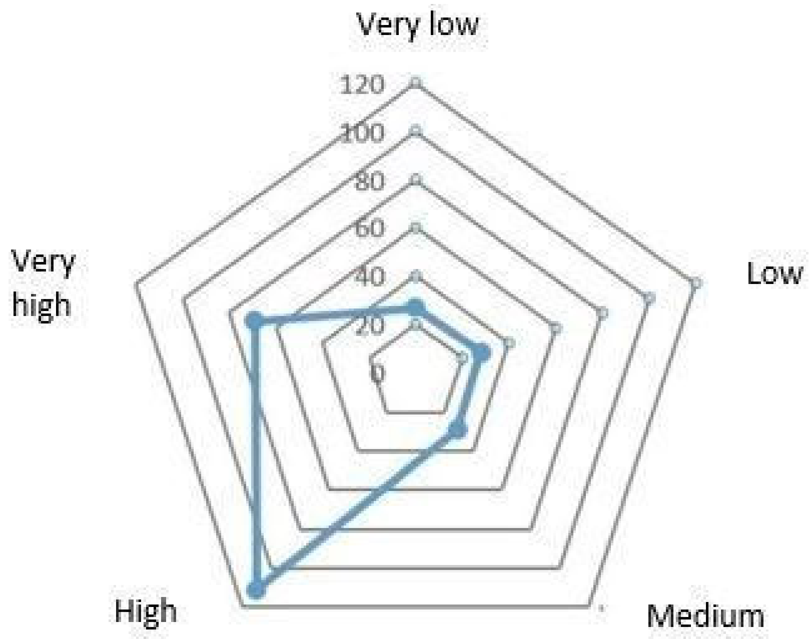


Figure 6. Mean effect of furniture on social interactions.

In general, the placement and arrangement of activities, green space, light and brightness, accessibility, and furniture are significantly correlated. Among these components, accessibility is the least effective variable influencing social interaction (as shown in Figure 7). While conducting the survey, the authors carried out a field observation to identify the existing physical components of territories. They also analysed the weakness of points with the potential to establish social interactions in a field study. Additionally, detailed information was illustrated based on the current layout and arrangement of spaces in Table 11.

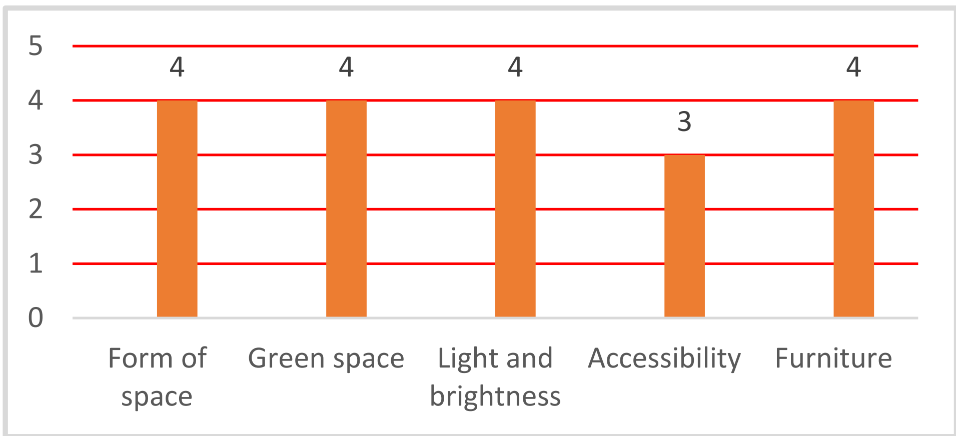
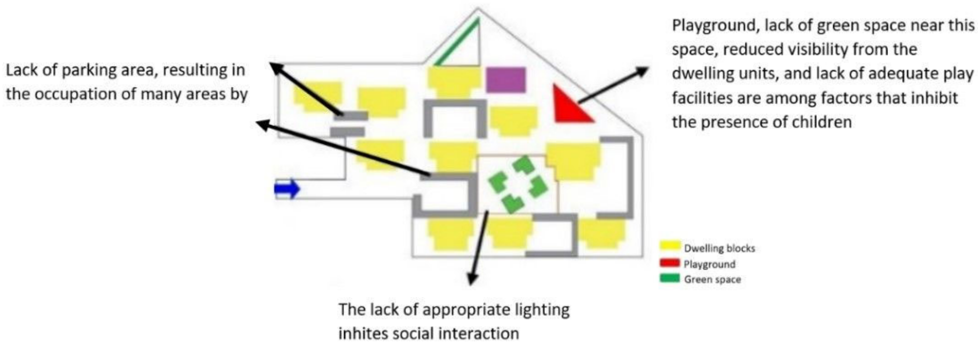
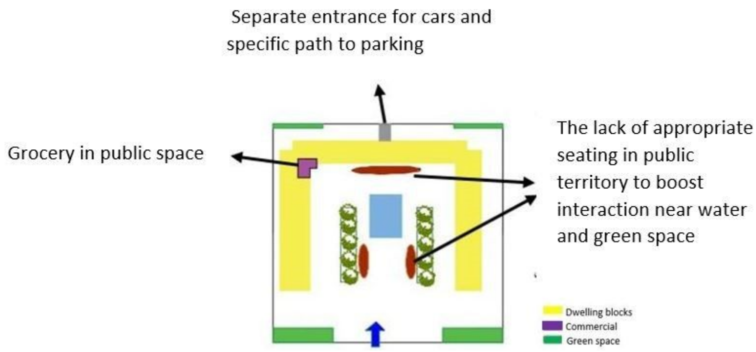
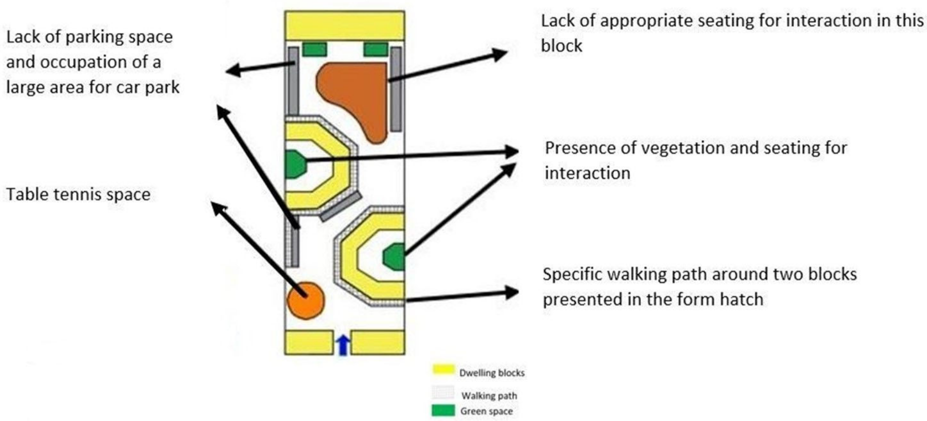
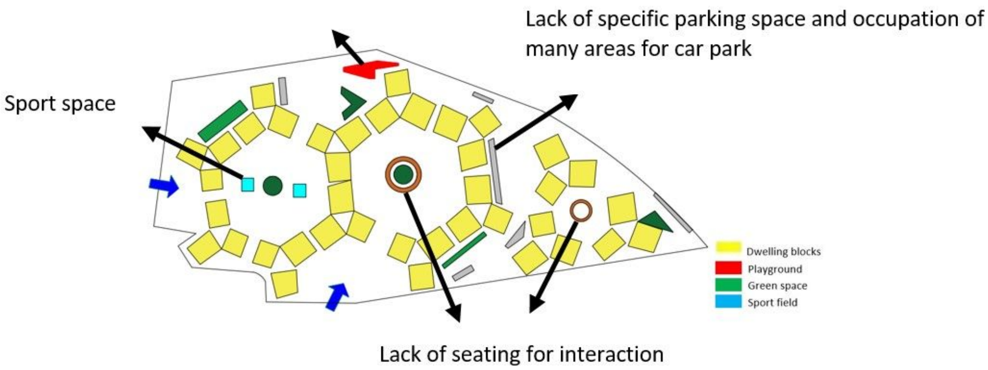


Figure 7. Significance of components from the perspective of respondents.

Table 11. The territories of the studied complexes.

Residential Arrangements	Different Territories
Clustered arrangement	
Linear arrangement	
Mixed arrangement	
Centralised arrangement	

5. Discussion

According to the findings, the segregation of spatial territoriality (public, semi-public, semi-private, and private) is among the factors influencing social interactions in residential complexes. The arrangement of things in space is an influential physical component of territoriality in social interaction. The formation, location, and shape of items in semi-public space of residential complexes affect the connectivity and users' use of these spaces. As specified by Huang [29], concave furniture around the playground or fountain can boost interaction between parents and children. Considering the current research results, another way to encourage peace is to create pathways and pedestrian paths around green spaces that are consistent with early findings [37]. The location of public spaces in the focal points of the yard and near residential blocks also affects social interactions. The research results indicate that green space is the second most effective physical component of territoriality in promoting users' interaction in semi-public areas of residential complexes. As another factor of territoriality influencing social interaction, this study examined the role of green spaces in users' motivation for communication with other users in residential complexes. Based on the findings, the decoration of green areas with a higher level of diversity in semi-public areas of residential complexes affects users' territoriality and may boost interactions between them. The findings are in agreement with past studies' findings [30,37]. In this regard, the separation of areas from plants has been considered a beneficial practice in past studies (such as [47]). Hence, a part of the courtyard can be designed with a diverse green space (e.g., a green space confined by boxes) as a place for newspaper reading, or it is possible to separate another part of the courtyard with shade trees and group furniture to make a place for chit-chat and communication. Designing such diverse green areas can encourage people to attend and participate.

Consistent with recent studies that advocate the role of lighting and brightness in encouraging users to interact [45,46], as physical components of territoriality, the impact of lighting and brightness on social interaction was evaluated. The results show that appropriate lighting and brightness can make the place attractive for communication. This is especially true in semi-public areas, such as courtyards. Sufficient lighting and brightness decrease fear of crime because users know that crime rates are higher in dark places. People are not willing to be in places without brightness and lighting. This means that appropriate lighting and brightness encourage users to attend and participate in the space.

This study assessed the impact of accessibility as a physical component of territoriality on changing user interactions in semi-public areas and residential complexes. The arrangement of building blocks, accessibility, and social interactions have a significant impact [60], but the present study suggests that accessibility has the least effect on social interaction change. This result, however, confirms that accessibility impacts user interaction, but its effectiveness is less than that of other components. Thus, the study results are consistent with past studies. In this regard, accessibility can improve social interaction when pathways or boulevards have a suitable width and length [37]. As a result, accessibility's low effectiveness in encouraging users to interact is due to unsorted and unsized pathways or lack of hierarchical access.

In addition, the results show that accessibility factors influence user interaction, which agrees with past studies [30,34,37,38,60]. The present study's findings revealed no significant relationship between the separation of pedestrians and vehicles, with the hierarchical component of accessibility to public space, and the location of public space and appropriate access to different places in residential complexes. This means that these components do not affect each other. Thus, removing, decreasing, and/or increasing the level of each of them did not affect their effectiveness. These factors are independent and have unique effects. Furthermore, the impacts of communal facilities were investigated in the current study. Residential complexes in Iran usually include outdoor seating, table tennis facilities, sports facilities, and gazebos in outdoor and semi-public areas. Facilities encourage users and residents to attend and participate in these areas. Such encouragement was facilitated by offering facilities for relaxation, meditation, running, fun, and a variety of physical activities.

The location of these facilities is significant because their location and spatial connections contribute to users' safety, fear of crime, peace, territoriality, and interaction with others. In this regard, past studies [40,47,48] have found that playgrounds located near blocks and green areas decrease the fear of crime in children and their parents. It, in turn, improves their motivation, activities, and interactions with other players. Children's outdoor activities can be enhanced when playgrounds are placed within the natural surveillance of dwelling units. Conversely, locating playgrounds without natural surveillance from dwelling units decreases the likelihood of children doing outdoor activities due to fear of crime. As a result, public spaces with convenient accessibility and/or located near central points will enhance residents' attendance and encourage participation.

In addition, the study observation revealed that the physical components of territoriality, such as hierarchical access and green spaces, as well as the way of organising elements and blocks, enhance legibility and a sense of invitation toward social interaction between users. This finding aligned with the literature [29,30,35,38]. According to the results, residential complexes with green spaces, light and brightness, access hierarchies, furniture, and elements create more motivation for social interaction. By contrast, residential complexes with clustered arrangements have not performed well in creating social interaction due to the lack of defined spaces and territories for people. Furthermore, multi-core, mixed, and linear complexes are able to define territoriality in several public and semi-public spaces. Accordingly, the second category can encourage residents to interact more than the clustered arrangement complexes. These findings are consistent with experimental research through a comparative approach using space syntax analysis by [37].

Human territorialities in historic neighbourhoods arguably were generated as a result of the existence of hierarchical spaces (i.e., courtyards and roads), which engendered osmotic borders, in conjunction with medieval socio-cultural activities, including intertwined spatial–political layers, such as power, traditions, gender segregation, ownership patterns, and ideological or blood-related backgrounds. Thus, semi-public courtyard roads functioned as the primary form of in-between spaces in historical Iranian and perhaps Middle Eastern architecture [96]. But urbanisation growth and a housing shortage changed current neighbourhoods' patterns and features. As a result, semi-public areas experienced deterioration when developers and planners excluded them from houses because of an urban land shortage. In this sense, the current study proved that a proper arrangement is needed for building blocks, hierarchical access, activities, and spatial decoration. It is in the courtyards and open spaces of residential complexes. Hence, as shown in Table 12, the following propositions have been provided; such semi-public spaces can potentially enhance residents' territoriality and facilitate their attendance, contribution, and interaction, including improving social cohesion and contributing to safety and satisfaction (Table 12).

Table 12. The proposed physical components for semi-public areas toward enhancing residents' territoriality.

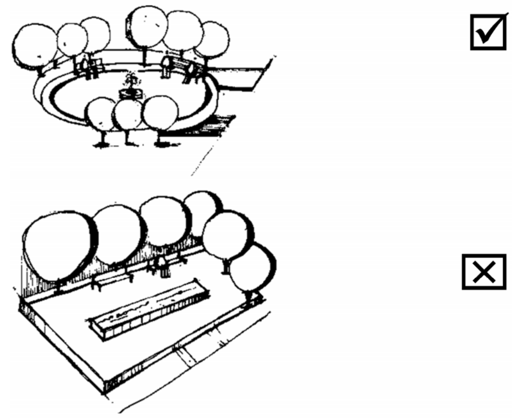
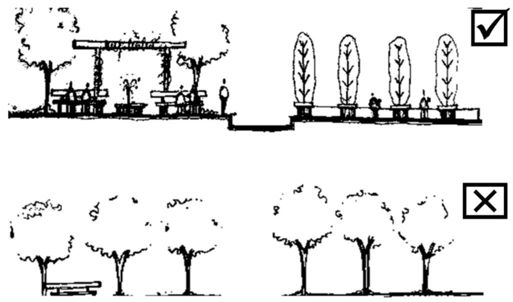
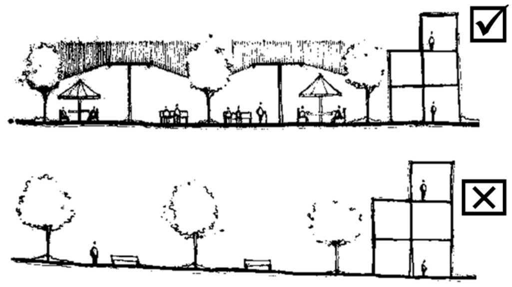
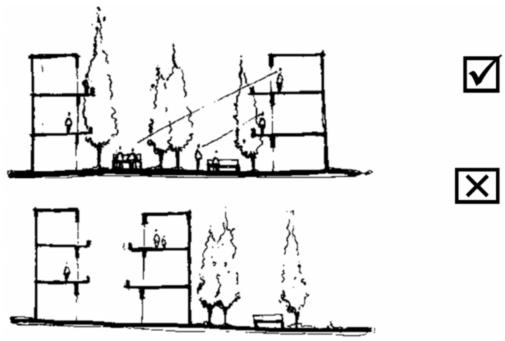
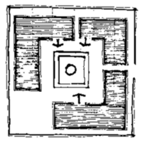
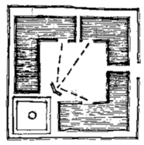
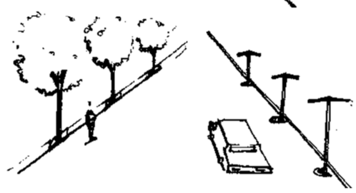
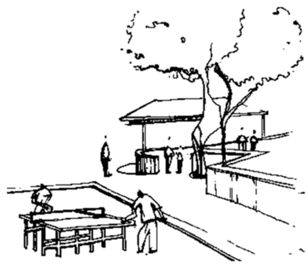
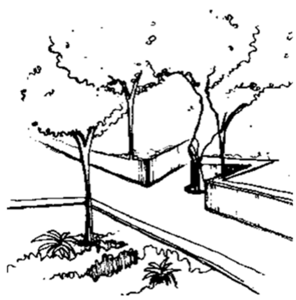
Index Physical	Component	Suggested Criteria	Appropriate and Inappropriate Samples
Form of Space	Form of furniture	Use of concave furniture around the fountain	
Green space	Green space diversity in different areas	Using diverse green spaces and defining different territories, such as spatial territories for study, a space with group furniture, and shade trees	
	Location of green space	The placement of green space in areas near the blocks with a view from the dwelling units enhances the presence of residents and social interaction among them	
Light	Light	Appropriate light in places with the potential for the presence of residents enhances this presence by encouraging the feeling of security	

Table 12. *Cont.*

Index Physical	Component	Suggested Criteria	Appropriate and Inappropriate Samples
Accessibility	Location of public spaces	Placement of public spaces in areas with easy accessibility and near the blocks	 ☑  ☒
	Separation of the pedestrian path from riding path	The separation of the pedestrian path from the riding path clarifies safe areas for making social interaction	 ☑  ☒
Furniture	Components, such as gazebo and table tennis facilities, and components related to social activities	The use of such components as gazebo and table tennis facilities in the courtyard encourage the presence of the residents	 ☑  ☒

6. Conclusions

This study aimed to investigate the influential physical components of human territorialities in semi-public spaces in four residential complexes and evaluate whether there is a significant relationship between human territorialities' physical components and social interactions. Based on human territoriality theory, the study was conducted with a mixed method using a questionnaire and direct observation in the four mass residential complexes of Shiraz, the third-largest city in Iran. The initial idea of this study refers to residents needing a place for living in peace, privacy, safety and comfort. Due to continuous migration from rural and small urban areas to major cities in Iran, such as Shiraz, they have suffered from ad hoc planning with confusion in decision-making that has resulted in turmoil in housing construction, and providing the proper infrastructures and public facilities in major cities.

Accordingly, serious issues have emerged in the physical aspect of cities, particularly neighbourhoods, in the past five decades. Housing, as the main cell of urban tissues, lacks the provision of previous functions for its residents as much as expected roles, such as well-being and interaction among residents of a residential complex. This is a result of the transformation of historic Iranian cities, such as Shiraz, and the result of social–spatial changes caused by the industrialisation of major cities, despite changes in residential neighbourhood fabrics occurring naturally, organically, and technologically in previous decades. The findings indicated that outdoor common areas arguably disclose socio-spatial mechanisms that once formed interactions of residents as members of a community and that once engendered satisfaction and physical activity in residential complexes. Lacking or inappropriate common areas in residential complexes results in isolation and exclusion among residents in residential complexes as relatively small communities. Negative impacts manifest in urban communities and higher levels, resulting in behavioural and communicational changes in the whole community.

Therefore, improving social interaction as a fundamental function is crucial in residential complexes. In other words, the existence and preservation of personalised territory and a sense of safety within that territory are the bases of everyone's social behaviour in the community. By discovering the correlation between human territoriality and physical activity, the association between neighbours' interactions and appropriate open space and shared facilities in the context of residential complexes proved to be crucial. Human territoriality, along with practical studies' findings, proved that current housing construction processes are inefficient in Shiraz and other major Iranian cities, have lagged far behind a deleterious process, have been physical-oriented, and are mostly concentrated on independent interventions, rather than considering the development process of communities. The present study revealed how human territoriality as spatial boundaries of individuals is formed based on the physical components of built areas (such as residential complexes), and the perceived spatial boundaries manage residents' behaviour to attend and contribute to an area or interaction with someone surrounding.

This redress in knowledge, that is, understanding perceived human territoriality and its social and physical implications, must be taken advantage of as a priority measure for the proposition of upgrading the quality of residential complexes in all Iranian cities. Hence, this study builds on previous research providing a useful case study insight that could be replicated in other countries/locations for comparison and influence the design of social housing spaces where human well-being, as part of sustainability objectives, is a priority factor for assessing design success.

Finally, this study discloses an idea for different stakeholders in the decision-making atmosphere to focus on building codes with a new perspective as human-oriented residential buildings that can redress semi-public spaces in residential complexes as an opportunity to increase residents' sense of belonging and to avoid migration and growing segregation.

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Article

Social Metabolism in Buruan SAE: Individual Rift Perspective on Urban Farming Model for Food Independence in Bandung, Indonesia

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Abstract: This study focused on one of the formulas for assessing social metabolism, specifically derived from individual variables. The formula was utilized as a framework for analyzing agricultural activities and combatting food vulnerability in urban communities. Bandung, the capital city of West Java in Indonesia, has implemented an urban agricultural program called Buruan SAE, using a policy formulation oriented towards food self-sufficiency for low-income citizens. This program utilized a policy formulation that involved using empty residential land owned by low-income citizens, distributing food to surrounding residents indiscriminately, and working towards anticipating nutritional vulnerability (stunting). However, the implementation had the opposite effect and pushed urban agriculture into becoming stagnant and undeveloped. This study aims to use individual rift theory as the analytic axiom to discuss the stagnation in the implementation of policy. The analysis was performed using a social monitoring method to form policy instruments that analyze Buruan SAE's stagnation in Bandung City.

Keywords: social metabolism; individual rift; Buruan SAE; policy instruments; urban agriculture; food independence

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1. Introduction

The availability of land for agriculture in big cities worldwide has always posed a significant challenge. However, unproductive lands, such as unused terraces and rooftops, can be used for agricultural purposes in anticipation of the scarcity of biological staples, which are increasingly difficult to obtain on the market due to economic reasons. This concept known as urban agriculture, has increasingly become a global issue that requires collaboration from various actors, including governments, the private sector, and community groups.

West Java is the second most populated province in Indonesia, with a population of 48,220,094 people, and Bandung City, which is the provincial capital, has a population of 2,530,000 and served as the focus of this case study. This is because its population is inversely proportional to the total agricultural land area for food production, which was only approximately 640 Ha in 2020. The decrease in agricultural land occurred due to the conversion into housing areas, shopping centers, offices, trading areas, and other facilities. This poses a threat to the productivity of agricultural output in terms of meeting regional food needs. Additionally, Bandung imports up to 96% of commodities required to complete the city's food needs from other regions.

To address this problem, a comprehensive implementation strategy is crucial, consisting of community-based solutions to fulfill food needs in urban areas. This is because the government's efforts are insufficient to make improvements or prevent the effects of increasing land conversion. These solutions are carried out by issuing regulations that ensure urban communities utilize the land or space in every house to grow various crop commodities (horticulture). By using land-saving agricultural designs with modern technology, these solutions can mitigate the consequences of unequal access to food and anticipate dependency on external sources. This approach also aligns with Sustainable Development Goals, particularly the goal of "Zero Hunger", which strives to ensure food security. The Provincial Government of Bandung has continued to actively promote the Buruan SAE program as a commitment to include food security in its economic development program. This pilot program focuses on an urban agriculture approach that utilizes unused land, such as terraces and rooftops, as suitable agriculture areas. The plants used are mostly vegetables, fruits, and medicinal plants, such as cherry tomatoes, kangkong, pak choi, chilies, and red ginger. This program is intended to overcome dependency on food imports and maintain community-based food stability and security in Bandung.

This study was conducted to address the question of how the Buruan SAE Program, over the past few years, has affected the problem of food insecurity. Through an evaluation conducted, this article also proposes an appropriate food distribution model to tackle the challenge faced by the program. To accomplish this, the target was first outlined based on the pillars of food security, namely, Availability, Affordability, and Utilization. Buruan SAE program is also closely related to the achievement of Bandung City Sustainable Development Goal number 2, called "Eliminate Hunger, Realize Food Security and Good Nutrition, as well as Improve Sustainable Agriculture". This was revealed in Mission Number 3 of Bandung City Regional Medium-Term Development Plan 2018–2023. It is also called "Realizing Advanced, Sustainable, and Equitable Economic Growth" with one of the strategies being "Realizing Food Security and Sustainable Urban Agriculture".

This article is based on the findings from the "Buruan SAE" or Urban Agriculture Evaluation Study, which analyzed the program's effectiveness in influencing people's behavior, and building awareness of urban agriculture as a step toward achieving food security and sustainability. The evaluation also considered the implications of changes in individual, social, and ecological aspects resulting from urban agricultural policy, which are important factors in the renewal of social and environmental conditions in the city. Significant attention was also given to the size of "separation/fractures" as a fundamental explanation of urban area development. These separations/fractures are based on the concept of exploitation encompassing land, water, space, and the potential of residents to carry out urban agriculture at their homes. This is important for the realization of urban agriculture to achieve the initiation, participation, and conservation renewal of natural and human resources in urban areas.

This measure of separation was used to examine the social implications of implementing urban agricultural policy, specifically adjusted to the lower-income community. Based on a previous study, the typology of urban agriculture found in Bandung City emphasizes subsistence agriculture for additional food supply to address scarcity during the pandemic era [1]. This adjustment was used to observe the improvement in the form of urban agriculture, which initially started as a public policy initiative and evolved into a culture implemented by the community. The implementation was achieved through social assessment methods and individual rifts in social metabolism to address issues of food availability, affordability, and utilization.

The measure of separation, derived from social assessment, served as a reference in examining the social implications of implementing urban agricultural policy. This is because subsistence farmers are predominantly supported by government assistance on a hobbyist basis only [1]. The discussion highlights the fact that personal pleasure is the major motivation for engaging in subsistence agriculture in urban areas. This perspective ultimately contributes to the stagnation of urban agriculture, making it challenging to foster new initiatives and improve governance. Therefore, there is a need to shift the focus toward increasing urban agriculture in Bandung City.

This study also considered various observations from previous practical studies on the phenomenon of urban agriculture. One of the strategies implemented was through a youth entrepreneurial approach to popularize, certify, and increase the number of urban agricultural activists [2]. However, there are certain obstacles to implementing the Buruan SAE program. For example, the national policy meant to support urban agricultural production has instead led to urban farmers returning to conventional agricultural processes, including the use of petrochemicals. This phenomenon diminished the contribution of urban agriculture and resulted in food scarcity [3].

Furthermore, a more in-depth discussion was provided regarding this topic drawing from previous studies. The discussion focused on how urban policy, particularly zoning and community empowerment policy in the form of MSMEs, significantly influence the development of settlement-based urban agriculture in Bandung. The fixation on vacant lands in the middle community settlements, especially in the pre-urban area, was explored. This paper also discussed the impact of dependency on residential vacant land and its implication for the sustainability of urban agricultural programs to involve more members of the community.

2. Theoretical Background

2.1. Urban Agriculture

The basic concept of urban agriculture revolves around producing, processing, and distributing food and other agricultural commodities through planting and animal husbandry in cities or metropolitan areas [4,5]. These three key aspects not only address food production problems but also encompass related economic, social, and environmental linkages [6].

Urban development, when not carried out comprehensively, can have detrimental effects on human health and the environment. To create optimal urban agriculture adjusted to promote food security and equitable distribution in low-income communities, it is essential to develop a model that addresses the destructive impact of urbanization [7]. The level of relative poverty can be identified from how a society fulfills its nutritional needs through the daily consumption of healthy products [8]. Prioritizing food production is crucial in improving the health conditions of low-income urban populations and reducing exposure to pollution [9]. In this regard, water clarity performs a significant role as a vital factor in the sustainable development of urban agriculture, especially in slum areas [10].

Furthermore, it is important to assess the presence of pathogens in agricultural inputs and consider other factors that affect livestock agribusiness along with external elements of production [11]. Substantial efforts are also needed to increase agricultural development for low-income societies in urban areas to reduce the cost of food consumption [12]. These efforts should focus on creating new production models that enable the establishment of independent businesses and facilitate the participation from low-income society who tend to experience social exclusion directed at community development [13]. This approach is beneficial not only for urban producers from low-income backgrounds but also for improving the quality of their products [5]. Additionally, ecological problems and environmental sustainability impacts are interconnected with the utilization of residential waste and the protection of natural ecosystems in urban areas.

The most tangible manifestation of urban agriculture is the utilization of unused lands for agricultural activities. From a structuration perspective, social practices, such as cultivating home gardens or buying food and seeds, are considered middle-level social structure practices within the broader framework, which includes the availability of household food and food production in urban areas and settlements. These practices, in turn, shape how individual actions in urban areas can be influenced and the association with the social structure of food availability [14]. The interaction between individuals and structures in urban plantations results in mediation processes formed between agencies (individual growers) and social practices (acts of gardening) [15]. It also involves conductors (actors) who deliver structural forms of food production (practices), contributing to household food supply in urban settlements [16]. Therefore, in conjunction with the concept of social structuring, urban agriculture brings about changes in the food production structure of urban settlements, which can be calculated based on a combination of (1) material (food), technology and infrastructure, physical entities (soil, topsoil, air, and water), (2) image (a symbol of urban agriculture), and (3) skills (competence, capability, technicality) [17].

2.2. Social Metabolism

Social metabolism is based on the concept that society needs to adapt to both natural changes and new conditions caused by the influence of economic structures (consumption-production) and social practice activities. These social activities can create artificial ecosystems that differ from natural ecosystems but are still interconnected. This concept of social metabolism highlights the distinction between artificial (social) and natural ecosystems [18].

Society performance, which is the basis for adjusting survival needs, can be utilized by the community in the concept of production and consumption [18]. It is affected by (a) the human economic situation, which is strongly influenced by population and economic growth, (b) the struggle for natural resources between various groups of people, and (c) differences in historical values by various groups, especially when there is an affirmation of their rights to the utilization of natural resources, both in the form of materials and utilization [19]. These factors serve as a framework for bringing about systemic change through critical analysis of society and the environment in industrial development [20], leading to the struggle for natural and human resources.

The discussion on urban agriculture also considered the concept of anticipating rural commodities, such as food, raw materials, and labor, which are processed into industrial waste [21], as a consequence of ongoing agricultural structures influenced by the green revolution [22]. This was closely associated with the patterns of land ownership [23] and led to continued dispossession through horizontal and vertical monopoly processes, and the use of chemicals in agricultural systems [24]. Therefore, urban agriculture provides an alternative to the green revolution, which aims to increase the impact of food commodities for all stakeholders within the production-consumption framework [25].

The metabolic rift provides a dynamic perspective that combines crisis and development theory, emphasizing capital accumulation, power struggles, and ecological changes in each phase of industrial development [26]. Perspective aiming to transform agricultural systems consider environmental and social sustainability by positioning material exchanges between society and nature through capitalist schemes and human alienation [20]. They also address the effects of industrialization schemes that lead to natural changes [27]. In the context of urban agriculture, the understanding of metabolic rift can be applied through the following perspective: (a) Ecological rift that leads to the reduction in chemicals in agricultural activities [28] through practical utilization of urban waste to support agriculture and overcome environmental crises [29]; and (b) Social rift that focuses on the changing patterns of agricultural production from social aspect including the transformation of agricultural work structures [30]. It acknowledges the reduction in agricultural cultivators in rural areas [29] and highlights alternative urban agriculture as a form of achieving non-formal food self-sufficiency in lower-class societies. Urban agriculture can enable independent food production and reduce the dependency [5] on the mainstream food market system in urban areas [31,32]; and (c) Individual rift, which explores the knowledge of food self-sufficiency based on the awareness of urban lower-class society on ecological issues and their food needs. These communities often experience alienation as a consequence of capitalism [33]. Urban agriculture serves as an effort by the lower-class society to create a variety of agricultural products, particularly organic ones, based on their preferences and the condition of the biophysical environment [34].

3. Materials and Methods

The evaluative approach was used in this study on Buruan SAE's public policy by taking a sample of middle- and lower-class society in 30 sub-districts in the Municipality of

Bandung. In general, data collection was carried out using the mixed method approach, wherein quantitative data were collected from 18 community members per sub-district through discursive questions regarding the food needs of urban lower-class society. Sampling was based on several question segments, which included a discursive portrayal of the correlation between food and the ecology of the lower-class society in Bandung City (based on ecological faults), the relationship between food and the domestic economy (based on social rift), and linkages between social motivation and local food structure (based on individual rift).

The input data consisted of respondents' perceptions reflected in their responses when questioned about residential agriculture (domestic garden), the form of residential agriculture to be made in their respective homes, and the social functions of the yard [34]. This was achieved using a social assessment method aimed at gathering specific perceptual information related to the main ideas of urban agriculture, namely, (a) food commodities that are safe for a community's healthy diets, (b) systematic production of natural food crops free from the domination of chemical elements, and (c) the cost of affordable food for the community.

These three main ideas would be aligned with various points of individual rift related to (a) human (individual) alienation from the results of their work in the context of food access issues. This knowledge was used to read the perceptions of respondents to understand the essential food commodities needed in the household. The main argument of the Buruan SAE program highlights Bandung City's dependence on food produced through the green revolution agriculture production system, which accounts for 96% of its food supply. The preferences of the respondents, particularly those living in the slum areas, can be used as data sources regarding the utilization of food commodities from the market to meet their household and community needs. These preferences also shed more light on their inclination to produce food, and the awareness about local food availability. Data collected from the respondents was used to explain the perceptions of the lower-class society in Bandung City regarding the connection between metabolic rift and Buruan SAE policy, which was formed as an initiation of urban agriculture. The urban agricultural aspect, segmented into three dimensions, social, economic, and ecological, was analyzed through the perspective of a metabolic rift. This was achieved by examining the relationship of individual, social, and ecological rift with the potential of achieving food self-sufficiency through the Buruan SAE. Another point related to individual rift was (b) the alienation of humans from their land or domestic garden. An in-depth analysis was used to explore the connection between the respondents and their respective domestic gardens. Based on the results, slum area domestic gardens in Bandung were less than 10 m^2. Therefore, gathering the perceptions of the slum area residents is crucial to ascertain their preferences regarding the ideal form of domestic agriculture. This includes determining what is considered adequate by the respondents, the communal usage of their yards, and the anticipated benefits for both the respondents and the community when domestic agriculture is implemented.

The elaborations of individual rift points were segmented into several questions contextualized on the conditions of the people in slum areas. These questions were aligned with the main dimensions of the Buruan SAE program.

Table 1 presents the three main ideas of urban agriculture developed through individual dimensions. The questions were adjusted based on the closeness between each point that corresponded to the aims of the three main ideas of Buruan SAE. The grouping of the input data aimed to classify discourse structures used as descriptions of how people living in the slum areas interpret and assess the necessity of urban agriculture. This data cluster was also used to analyze the suitability of implementing policy instruments in improving food availability. The color of each question column corresponds to the variable in Table 2 and the input data in Table 3.

Table 1. Segmentation of questionnaire question points based on the access of individual and urban low-income communities to food (options are the words in parentheses).

Individual Dimension	Main Questions	Questionnaire Points
Individual Social Role	Usage Purpose	What is the use of the respondent's yard? (ornamental garden, domestic pharmacy, garage, storage, play area, and not in use)
	Social Purpose	What are the forms of respondents' yard utilization for community needs? (religion, park, government services, policy outreach, socio-economical asset, public order, and ecological preservation)
	Social Implication	What are the beneficial impacts of using the yard? (high moral society, compact society, resolved community problems, more accessible actual news, empowered community economy, public order, and environment preservation)
	Dominant Deviation	What are the beneficial impacts of using the yard? (high moral society, society awareness issue, resolved community problems, more accessible actual news, empowered community economic condition, public order, and ecological preservation)
	Social Respond	What are responses toward community service? (fully supported, sufficient, still searching for reasons, allowance, limited, and ignore)
	Yard Priority	What did the respondents consider mostly for the use of their yard? (adding park houseplants, adding medicinal plants, garage, storage, playground, and domestic food garden)
	Space Consideration	What is the most considered use of their yard? (aesthetic/beauty, function to solve problems at daily domestic business, biodiversity, benefits for society, and additional economic income)
	Individual Respond	What are responses on the importance of community service taken by the respondents? (it should be continued because it is imitated by the community and receives adequate support; it should be continued as long as the community accepts it; it should be continued if it does not disturb the community, reduce community service because it is rarely implemented, concerned that social action will disturb the community, and stop community service)
	Individual Contribution	How did most of the respondents solve the problems of the surrounding community? (Embracing problematic individuals to serve the community, inviting neighbors to carry out joint activities, volunteering in disasters, becoming the main informant for the community, opening up business opportunities for local neighbors, creating public order, and maintaining the beauty of the environment)
	Yard Access	How wide is the respondent's yard? (0–100 m^2)
	Space Utilization	What kind of planting should the respondent establish in his yard? (walls of buildings, water tanks, and available yards)
Individual and Community Food Access	Instructional Respond	Which are the main factors respondents consider when asked to review community food access? (get enough food, nearby groceries, clean and natural food, preserved food, and food of good physical quality and taste)
	Healthy Agriculture Consideration	What did most of the respondents consider in carrying out yard agriculture with healthy food commodity results (buying agricultural equipment from distributors, obtaining agricultural equipment from their closest relatives, receiving agriculture equipment from the government, and making agricultural equipment themselves)

Table 1. *Cont.*

Individual Dimension	Main Questions	Questionnaire Points
Individual and Community Food Access	Natural Agriculture Consideration	What did the respondents consider in carrying out home garden agriculture with natural food commodity results? (buying organic agriculture equipment, getting organic agriculture equipment from relatives, getting organic equipment from the government, and making organic agriculture equipment independently)
	Economical Agriculture Consideration	What did the respondents consider for implementing domestic gardens with economical food commodity results? (buy cost-effective agriculture equipment, get organic agriculture equipment from relatives to save costs, obtain equipment from the government for cost-effectiveness, and manufacture agricultural equipment independently to reduce costs)
	Healthy Agricultural Perception	What are the respondents' perceptions when asked to practice healthy home gardening? (the need for pesticides, quality fertilizers, availability of water, fertile soil, and less chemical requirement agriculture methods)
	Healthy Product Advantages	What are the benefits received by the community from the results of healthy food production carried out by the respondents? (absence of pests, high nutrition, yields look fertile, and outward appearance of the yields look convincing)
	Natural Agriculture Perception	What are the respondents' perceptions when asked to practice natural yard agriculture (natural methods of pest control, availability of natural fertilizers, availability of clear water, fertile and organic soil, and zero-waste yard agriculture)
	Natural Product Advantage	What are the benefits received by the community from the results of organic food production carried out by the respondents? (absence of pests, high nutrition, the appearance of the crops looks fertile, and the appearance of the crops looks convincing)
	Economic Agriculture Perception	What are the respondents' perceptions when asked to carry out economic yard agriculture? (cost-efficient methods of pest control, availability of fertilizers at affordable prices, availability of free water, cost-effective soil media, and profitable zero-waste home gardening)
	Economical Product Advantages	What are the benefits the community receives from the results of economic food production carried out by the respondents? (reasonable price due to the absence of pests, high and inexpensive nutrition also, crops look fertile, cost-effective, and have economic value)
Individual participation and expectations on food availability issue	Usage Prediction	What land area should be used for practicing house-yard agriculture? (1–4, 1/3, 1/2, or 3/5 of the respondent's yard)
	Product Distribution	To whom will the respondent send agricultural produce primarily from his home yard? (Elder members, low-income community members, social institutions, malnourished people, closest relatives/nearby society, and customers at the market)
	Nutritional Implication	What are the expected impacts of yard agriculture activities on the malnourished community? (Participating in carrying out yard agriculture, prioritizing babies and small children, eradicating food difficulties, and helping respondents to develop yard agriculture)
	Discontinuity Consideration	What factors discouraged the respondents from agriculture in their yards? (stagnated knowledge of agriculture, crop quality is stagnant, yard agriculture activities disturb the community, the community does not need the respondent's harvest, there is no social media coverage of the domestic garden result, and the financial income of agricultural products is below expectation)
	Agricultural Skills	How can the respondent develop their backyard agriculture (development of agricultural skills, quality yields, development of garden with good impact on people's welfare, highlighted by the media, and economic income)

Table 2. The context variable is the perceived resilience of low-income urban communities to food self-sufficiency through food accessibility.

Metabolism Rift	Social Dimension **	Economical Dimension **	Ecological Dimension **
Individual Rift *	Usage Purpose	Yard Priority	Yard Access
	Social Purpose	Space Consideration	Space Utilization
	Social Implication	Individual Contribution	Healthy Agriculture Perception
	Dominant Deviation	Individual Respond	Healthy Product Advantages
	Social Respond	Instructional Respond	Natural Agriculture Perception
	Usage Prediction	Healthy Agriculture Consideration	Natural Product Advantages
	Product Distribution	Natural Agriculture Consideration	Economic Agriculture Perception
	Nutritional Implication	Economical Agriculture Consideration	Economical Product Advantages
		Discontinuity Consideration	Agricultural Skills

= Individual social role, = Individual and community food access, = Individual participation and expectation. * Each column includes the main question in Table 1. ** Each main question is segmented based on the dimensions of the Buruan SAE program.

Among the total 540 respondents that participated in this study, 56% had a low income of IDR 100,000—IDR 1,500,000 per month (max. 99.58$ USD), 27% had middle to lower-income of Rp. 1,600,000.00—Rp. 3,000,000.00 per month (max. 199.16$ USD), and 17% had a middle income of more than Rp. 3,100,000. Furthermore, 62% of the respondents did not have a side job, 12% and 11% were engaged in shop businesses and online sales, respectively, and another 15% had non-permanent jobs, such as procurement, project, and freelance. Approximately 71% and 10% spent Rp. 100,000—Rp. 1,500,000 and more than Rp. 2,500,000 per month on food needs. This data proved that the respondents were predominantly from low- and middle-income societies, spending 83% of their accumulated income and 84% of their monthly expenditure on food. This explained why urban lower-income society continued to gain access to food despite facing weak economic capabilities.

The relationship between the dimensions of Buruan SAE and the metabolic rift was equated with a policy design based on a contextual review [35] through certain stages. These stages include (a) understanding legal documents, (b) gaining knowledge of policy through documents such as the BIUF (Bandung Integrated Urban Agriculture) booklet, (c) documenting DKPP apparatus discourse through FGD actions, (d) administration of program evaluation questionnaires to Buruan SAE Gardens Group agency, (e) carrying out short interviews with 30 sub-district economic and development officers in Bandung City, (f) semi-qualitative data collection of urban low-income society through discursive questionnaires, and (g) collecting semi-qualitative data from representatives of 12 SKPD (Regional Work Units).

These steps were used to link the dimensions of Buruan SAE policy with metabolic rift based on the context of citizen safety (community resilience) [30]. This approach demonstrated the public's perception of the policy as an urban food security program oriented towards food self-sufficiency. By adopting the Natural Based Solutions Instruments approach, with social monitoring as an output to examine the community perceptions in discourse [36], food security was interpreted by the low-income society based on their actual daily lives [36,37]. Consequently, data were obtained for the implementation of the "Buruan SAE" urban agriculture policy.

Table 3. Social monitoring about the discourse of food independence in the low-income society of Bandung based on the review of Buruan SAE Individual Rift using the two largest options or >45%. Read vertically per column.

Social Dimension	Economical Dimension	Ecological Dimension
57% Ornamental garden and storage	75% Prefer to develop gardens and park	70% Area of yard is approximately 10 m^2
56% Park and socio-economical asset	60% Prioritize the beauty and function of the park	69% Decide to plant in the yard
45% Restoring the environment and economy	55% Urging to cooperate and improve the quality of the environment	59% Prioritize healthy fertilizer and high-water content
49% Lack of economic condition and societal awareness	55% Continuing social actions	49% Prioritize the absence of pests and organic consumption
53% Supportive and interactive toward social actions	54% Focusing on affordability and food quality	54% Prefer natural fertilizer and clean water
74% About to plant in 1/4 until 3/5 of the total yard area	51% Obtaining tools from distributors and partners for healthy food production	71% Prioritize food that has high nutrition and is free of pests
53% About sharing the results with nearby society	53% Purchasing agricultural instruments or creating natural food instruments	56% Prefer affordable fertilizing method and free cost of water
67% Expect no more lack of food and active participation from vulnerable society	53% Purchasing agricultural instruments or creating economic food instruments	63% Prefer affordable high-nutritional food and interesting display
	65% Stop agriculture in a yard if the progress experience stagnancy and disturbing	54% Expand agriculture areas if the result is good and impactful to society

= Individual social role, = Individual and community food access = Individual participationand expectation.

The data segmentation points in this table were derived from the grouping of information through the acquisition of qualitative data (public discourse) regarding the metabolic rift in the local food system in Bandung City. These segmentation points were obtained by the Enumerator of the 2022 Buruan SAE Policy Evaluation Research. This study involved 18 underprivileged respondents in 30 districts and aimed to examine the relationship between urban low-income society and their access to food [38] and food perceptions [34] through social monitoring methods [8]. Furthermore, the segmentation points for this table column obtained from the three policy dimensions in the Buruan SAE program were adjusted to the provisions of the Mayor of Bandung in Circular Letter Number 520/S.E.086 concerning the Implementation of Integrated Urban Agriculture Activities (Buruan SAE, Healthy Natural Economics) and the normative concept of urban agriculture [39]. Other segments incorporated in data processing were discussed through concept mapping of the description based on the indicators in Table 1. These indicators were used as one of the data matriculation materials for the implementation of Buruan SAE as a policy entity to be reviewed (Figure 1).

The discussion of results will focus on presenting the analysis and segmentation of data, specifically related to the implementation of Buruan SAE policy from 2018 to 2022. The aim is to explain how Bandung City's urban agricultural policy can be adapted to address individual rift in urban social metabolism of the public. These two data will demonstrate the role of urban agriculture in improving access to food and facilitating self-sufficiency.

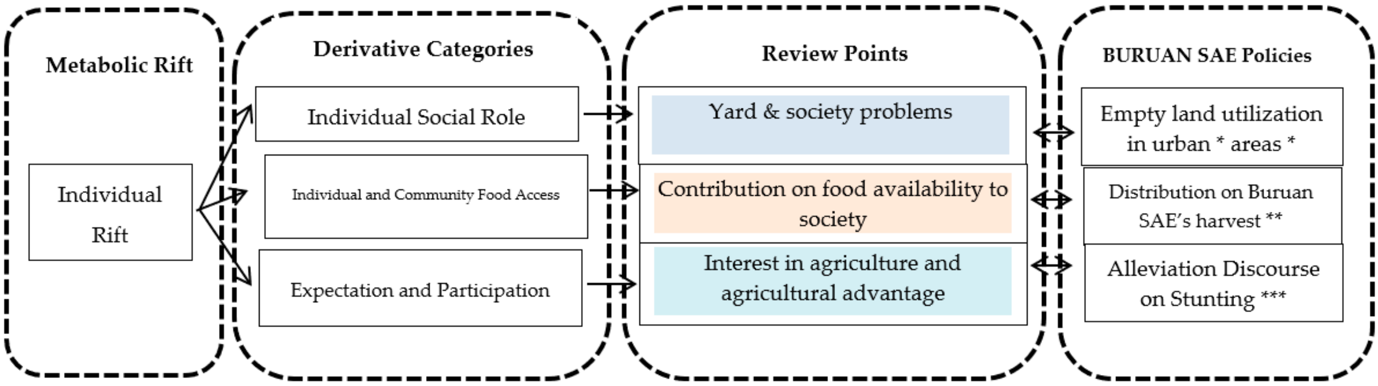

Figure 1. Framework-based thinking metabolic social rift of "Buruan SAE". * = Buruan SAE social dimension, ** = Buruan SAE economical dimension *** = Buruan SAE ecological dimension. Each point in Buruan SAE Policies is a derivative of Derivative Categories taken from Individual Dimensions in Table 1.

4. Results

The results present the most relevant data on the metabolism of urban communities in the context of food self-sufficiency as an outcome of implementing local food systems and also in line with urban ecology [7,40] of Bandung City. The explanations presented through tables will guide critical analysis, enabling the contextualization of Buruan SAE policy instruments within alternative policy forms that analyze specific rifts in social metabolism [41].

Individual rifts of urban agriculture that appear in the social dimension can be understood through the perceptions of the lower-class society. This segment of society still follows the idea of using home terraces, which has emerged as the prevailing discourse on alternative spatial planning in Bandung City. It aims to address issues, such as urban density, the impact of expansion on residential areas, and the growth of industry and service sectors [42]. For the urban lower-class, the growth of industry and service areas is still closely associated with social relationships within settlements. These settlements often adhere to slum area spatial policies, such as road repairs, irrigation improvements, provision of waste sites, and evictions aimed at relocating lower-income society [43]. Policy, which prioritizes the existing facilities in slum settlements and building structures, including security, safety, health, and overall comfort of building structures. Furthermore, the densely populated settlements in Bandung, characterized by high building coefficients between 80% to 90%, and the presence of valuable land, especially in core areas designated for service administration buildings [44], further complicate efforts to create residential areas equipped with adequate yard gardens. The existence of slum areas with leapfrog development cases resulting from linearly following the highway line drawn from the city center [45] also adds to the challenge of establishing residential areas with sufficient yard space. This situation is further exacerbated by the dominant preference of the lower-income society to utilize vacant areas not only for gardens but also for warehouses to store goods in a narrow area, according to the Basic Building Coefficient.

Personal aspirations and initiatives towards socially oriented stimulation, which have almost passed the average point (56% and 49%), are gaining popularity among urban lower-class individuals who face below-average environmental conditions, low-incomes, and low economic development (45% and 49%). This indicates social structure influenced by the prevailing development discourse focused on public infrastructure and driven by the PPIPK+'s program. However, this popularity has not yet translated into a widespread orientation in urban planning and design that prioritizes food self-sufficiency and the use of yards. It is also confronted with the discourse on improving public infrastructure based on the 'orientation without slums' approach. The lack of integration between the applied concepts of urban agriculture along with the addition of infrastructure through PPIPK+, which primarily focuses on the agricultural training for garden groups, creates a disconnect. This separation affects the essence of urban agriculture as a means to achieve self-sufficiency in food availability by procuring infrastructure facilities as part of the city's spatial planning efforts. Bandung City government has prioritized subsistence farmers within the plantation group for development [16], but this approach has not yielded significant achievements in reducing household expenses, particularly on food [46]. The contextualization of market schemes based on agricultural costs and certification [47] also presents obstacles for DKPP to conduct further studies on implementing urban agriculture in densely populated residential areas. The establishment of successful urban agriculture initiatives is more feasible through the involvement of investors, who can utilize the ample vacant land in peri-urban areas for productive agricultural purposes [16] (Figure 2).

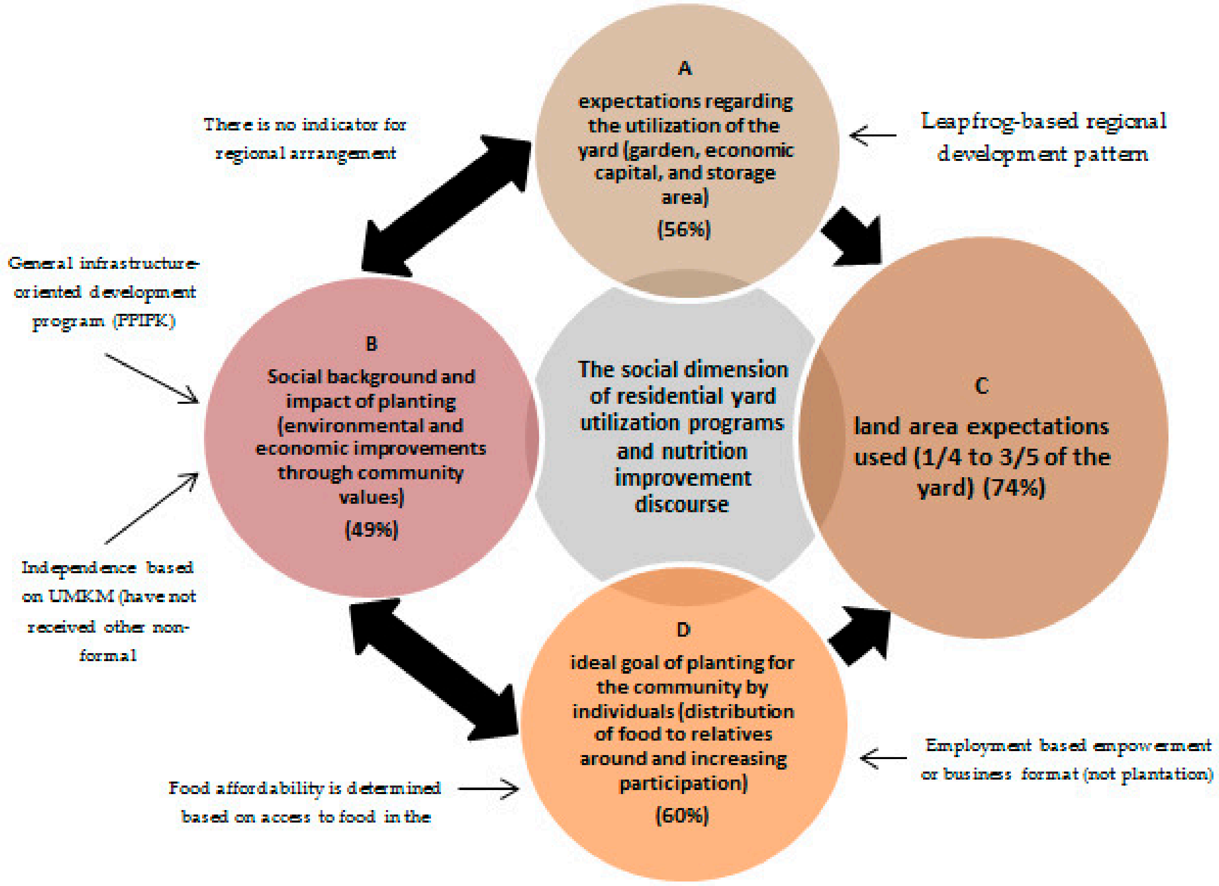

Figure 2. The suitability of implementing the Buruan SAE program and fostering an interest in planting in the social dimension is influenced by the individual rift. The slice of each circle is influenced by the percent number at the main point.

This condition has an impact on the status of food self-sufficiency and the inclination towards independent food cultivation, which no longer focuses on urban agriculture for vulnerable members of society, including the lower- and lower-middle-class. There is instead a discourse based on aspects of affordability, namely, the ability to buy food in the market rather than produce it themselves [48]. Although urban agriculture is a non-formal approach to reducing food dependency through exchange transactions and less reliance on agro-industrial producers [26], it should also prioritize empowering vulnerable societies to independently determine the flow of food production and consumption [14]. When implementing policy, it is also necessary to consider social networking factors, which are closely intertwined with the discourse on prioritizing the economic development of vulnerable societies. This emphasis is more focused on accelerating economic growth either through wage-based employment or enhancing independent capital for MSMEs, and improving the quality of settlements.

Based on an individual rift in the economic dimension of Buruan SAE policy, the interest in developing residential aesthetics along with cooperation among urban lower-class society is influenced by the city's expansion. Approximately 20% of the sub-districts are considered extreme slums in urban basin-based settlements. Moreover, the increase in land prices, driven by variations in land use, adds to the challenge [49]. This creates a perception that yard engineering in the form of a useful garden takes precedence over the urban plantation. The discourse on using gardens and parks to address residential environmental problems in Bandung City with a focus on risks, such as air pollution, floods, greenhouse emissions, and water scarcity, is considered a priority, accounting for 75% and 60% of the efforts, respectively. In contrast, other disasters, such as limited access to food due to drainage difficulties, complicated management of clean water access facilities from underground springs, household waste management, the number of vehicles, and greenhouse and industrial pollution, are given less priority.

Urban settlement systems, particularly in slum areas, aim to improve the environment through various patterns [49]. These patterns are focused on enhancing the exchange of value from raw to processed materials, primarily within the food processing industry and production schemes. Urban society's waste generation resulting from the material production chain is considered a consequence of this system [8].

Buruan SAE's economic policy aims to reduce dependency on commercial food from conventional markets by promoting the use of home terraces as green open spaces. This policy was adopted because backyard plantation schemes have not been able to address the phenomenon of urban food industrialization. Therefore, agriculture activities have remained primarily private initiatives for those who can manage the land [40]. Even the Urban Farmer Group, while contributing to massive food alleviation efforts, cannot be viewed as a comprehensive solution unless there is a local food system model that focuses on establishing a household-based food production chain. This approach should be adjusted to local-scaled economic goals, taking into account the population density of each city area, and be linked to addressing regional food vulnerability [25].

Although the previous literature mentioned that urban land agriculture initiatives were carried out by the community, it is necessary to highlight the key societal elements serving as the main pillars of the continuity regarding Buruan SAE program in respective regions. After many people, especially homemakers, felt the unsustainable impact of urban agriculture in 2021–2022 (Post-COVID-19), the function of garden planting and maintenance activities has been given to an all-in-one government agency named GOBER (Golongan Bebersih/City Cleaning Officer). This agency, which is responsible for maintaining the cleanliness of cities in their respective areas, has been assigned to continue the task of caring for urban agriculture under the direct instructions of sub-district officers.

This finding contradicts the manifestation of agricultural activities in urban settlements, which are often based on hobbies, especially among women. For instance, the Sa'uyunan Gardens Group, which initially engaged in the processing of garden produce, faced stagnation due to the absence of certification and a lack of efforts to sustain the initial agricultural activities led by homemakers. Consequently, more land was taken over by GOBER [16]. The focus on urban agriculture has shifted towards processed products which are not fully supported.

The implementation of urban agriculture lacks a local food system design that bridges the gaps between urban agricultural policy [11,50]. These policies fail to consider the calculation of commodity production per settlement, leading to public perceptions that prioritize food availability from nearby markets. The emphasis is placed more on the appearance of food as a measure of success for economically vulnerable urban individuals. A more valid solution would involve calculating measured needs and strengthening food consumption through the closest access point. This approach provides a means to anticipate limitations in nutrition rather than relying on unpredictable sources and lacking knowledge about food production through alternative systems. The benefits of the Buruan SAE harvest should be distributed to the surrounding society, taking into account the urgency of receiving the harvested products.

This value also influences the perception of low-income urban individuals, motivating them to engage in agricultural activities using organic methods. The motivation stems from considering the costs associated with implementing food agriculture in their settlements, which has an average value of 52.3%. Therefore, the availability of water in urban areas and the presence of fertilizing components (fertilizers) are important factors to be taken into account. These factors complement the absence of fixed prices for residential plantation crops in each commodity, which is due to the lack of advanced agricultural technology compared to the food industry scheme typically seen in rural agriculture [51,52]. Furthermore, the absence of a budget allocation for procuring facilities, even with a budget of IDR 100,000,000 from PPIPK+, and the lack of agricultural stimulus per household from DKPP for urban agricultural activities in densely populated areas, contribute to higher production costs. This consideration makes the potential income from urban agriculture uncertain. Therefore, doubts arise among urban raw food producers regarding the consistency of their agricultural actions. They are concerned that their activities may be discontinued without providing nutritional and economic benefits during the agricultural process [36], as experienced by 65% of the respondents (Figure 3).

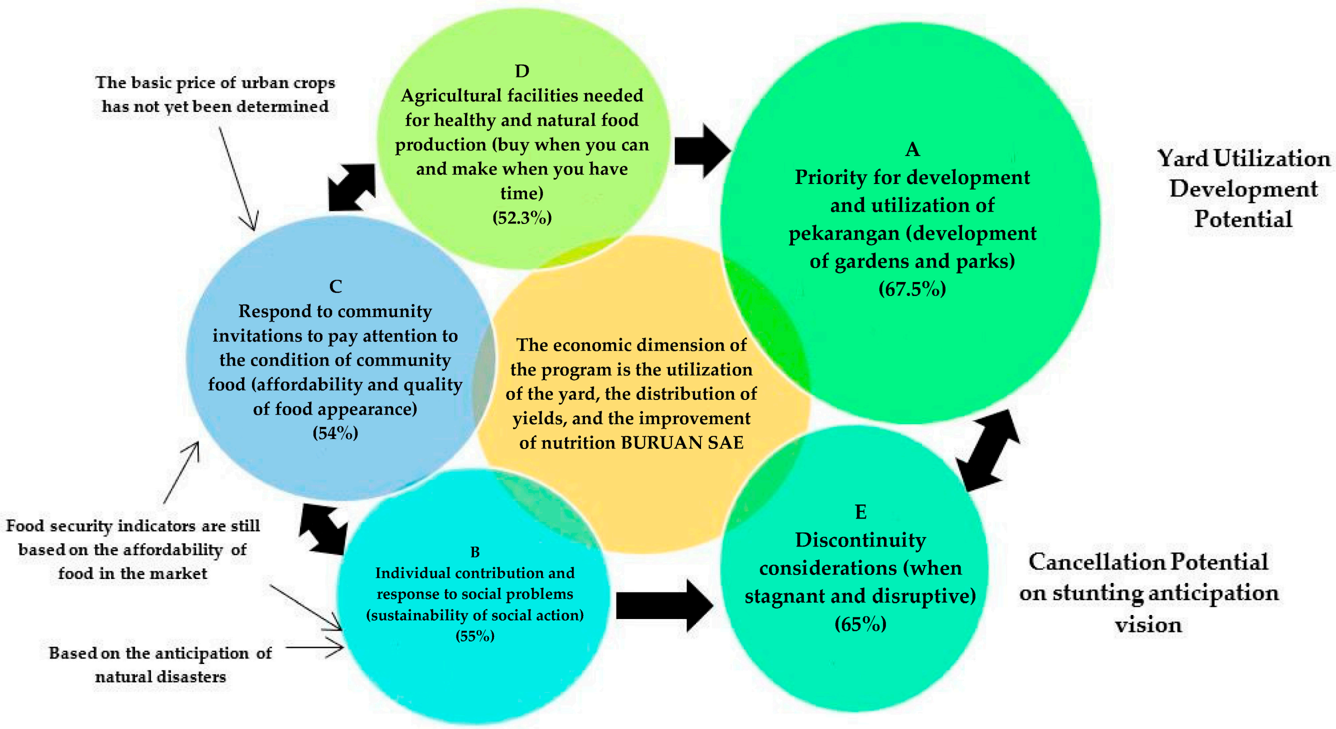

Figure 3. Components of the individual rift that affect the suitability of implementing the yard utilization program, harvest distribution, and stunting alleviation in the economic dimension of Buruan SAE. The slices of each circle are influenced by the percentage at the main point.

Based on individual rift in the ecological dimension, the use of yards less than 10 m^2 in area, is the last resort in activating residential plantations in densely populated areas. According to the data from DPKP3, the percentage of building coefficient utilization in densely populated residential areas has increased from 42.45% in 2018 to 46.33% in 2020. Considering the minimal empty spaces mandated for each building unit in the Basic Building Coefficient, plantations with minimal land are seen as the potential solution for urban agriculture. Respondents from urban lower-class society preferred planting in their yards rather than implementing alternative land-efficient agriculture. This choice was influenced by factors, such as costs and the perceived risks associated with land-efficient agriculture systems, which might be difficult to manage, as stated by 69% of the respondents.

However, despite the importance of utilizing empty spaces, there has been a lack of planning for the development of land-efficient plantations in line with the Basic Coefficient of Buildings. This oversight disregards the RPKD DPKP3 document (Household and Settlement Area, Land and Landscaping Office of the City of Bandung), which serves as an indicator of service for settlement arrangement and empowerment in slum areas. The absence of objective adjustments to address the challenges faced by urban lower-class citizens, who experience a serious metabolic rift, restricts them to utilize only their housing space [7]. This limitation arises from the weak utilization of low-value buildings due to the increasing exchange rates and declining soil fertility in urban areas [20].

In line with the absence of a well-defined approach for growing healthy, cost-effective, and natural crops, various perceptions and objectives have emerged regarding the implementation of urban agriculture. These perceptions are based on respondents' understanding of ecological aspects and predominantly revolve around the cultivation of healthy produce. This can be achieved using quality organic fertilizers and pesticides that are environmentally friendly, as stated by 59% of the respondents. Furthermore, there is a focus on plant fertilizers that increase nutrients without synthetic components and the availability of clean water for natural crop yields (54%). There is also a demand for affordable fertilization procedures, along with an accessible and cost-effective water supply system (56%).

The overall perception with an average of 56.3% in the category of actualizing individual plantings contributions to a local food system highlights the need for a planned planting method comprising: (1) The Availability System for Organic Agriculture Components, which are provided for the low-income society. This can be actualized through policy instruments focused on the mechanism for providing organic facilities and ensuring the availability of clean water [10]. The systematic nature of this approach aligns with the conditions faced by an urban lower-class society, which may struggle to provide organic agriculture facilities and infrastructure due to the difficulty in manufacturing processes [25] and the requirement of various complicated components [21].

DKPP needs to consider a decentralized constant supply action driven by the specific agricultural requirement per region. These requirements differ based on the settlement density and the average context of the difference in basic coefficient among buildings per sub-district, and the availability of empty yards; (2) The use of varied oriented planting systems, driven by different diversity of plant units per region, and supplement needs and doses depending on the resistance levels [26]. The plant resistance is highly influenced by factors, such as the temperature and height of the region, which are determined by the geographical structure of Bandung, characterized by its concave shape; (3) The need for policy implementation in slum areas on the use of urban residential water and its connection to agriculture [53]. This requires a specific design for governing access to urban agricultural water sources along with the provision of supervision and engineering support for affordable soil fertility through routine disbursement, such as mulching. The implementation of routine disbursement should be agreed upon through the collaboration between DKPP and DPKP3, particularly in terms of clean water facilities for urban agriculture. Additionally, vacant land areas can be used for the organized regeneration of the biological components in the soil. This approach is useful for various forms of urban agriculture ranging from using media pots and yards to hydroponics with the aim of minimizing the expenditure cost of planting among urban low-income societies.

However, this perception requires the support of more comprehensive policy instruments, namely, Buruan SAE, to address the conditions of slums and ensure access to natural and human resources needed in supporting urban agricultural actors [29]. This action can help the residents to organize more measurable food distribution programs and face the challenges of agroindustrial production through urban agricultural standardization [54]. The previous efforts carried out by the DKPP to transport agricultural produce from the headquarters led to the perception of centralized governance over empty urban spaces.

Modeling has been conducted in Bandung City since 2019, leading to centralized urban agricultural actions and the utilization of land based on the Statement Letter from the Mayor. This approach has resulted in limited outcomes, primarily focused on the sharing of yields, without clear objectives regarding the implications of its implementation. Consequently, conflicts over land usage often occur due to the absence of a legal process in the use of plantation land during community settlements. This uncertainty has caused many urban agricultural practices to relocate from their initial location or even cease altogether due to the unavailability of certain areas. Based on the survey conducted among low-income citizens, the agricultural cost is influenced by several factors. These include the availability of free organic pest control (49%), the production of nutritious and undamaged products (71%), and affordable prices of products for low-income citizens (63%). These findings highlight the main expectation of urban agricultural actors. With an average rate of 61%, the survey demonstrated that the respondents prioritized meeting their metabolic needs rather than focusing solely on the quantity of harvest. This emphasis on meeting nutritional needs is important, as low-income citizens are often confronted with the risk of malnutrition and limited access to proper food [7], and little knowledge of nutrition due to poverty [55].

According to 54% of the respondents, the expansion of urban agriculture in each residential yard serves as one of the indicators of low-income citizens' capability to control the flow of food production. The impact is not the final implication of realizing urban agriculture, but it can be used as an indicator to eliminate food scarcity because home-grown products are considered independent production (asset) for each citizen. Therefore, as the number of home-grown agriculture activities increases, the citizens become more aware and knowledgeable about various and complex processes. This can improve the capacity of each citizen to become more independent, efficient, and effective in fulfilling their nutritional needs [54] (Figure 4).

Based on the findings from social, economic, and ecological aspects, the composition of the analysis proved that the result can be analyzed from the perspective of individual rift regarding food access conditions in Bandung City. This analysis was predicated on the implementation of the Buruan SAE program as the main policy for urban food availability (Figure 5).

Based on the individual rift' perspective, there are three dimensions of urban agricultural structure policy: (A) To formulate a policy that reorganizes slum area design, policy itself must be based on the indicator of development, such as food independence. This new indicator is related to the performance provided by Bappelitbangda, DPKP3, and DKPP to low-income citizens from slum areas. The performance can be evaluated based on the indicator of achievement and success in the Food Availability Program as one of the objectives in the Sustainable Development Goals of Bandung City; (B) The indicators to detect threats to city development, such as the risks of natural disasters and economic vulnerability, are not sufficient. There is also a need to include indicators that reflect the limited access to food availability and ensure the sustainability of food proportion, production, and consumption among low-income citizens per district. This will lead to the creation of alternative economic activities with more concrete objective measures to fulfill the needs of nutrition for each district; (C) Without understanding the specific requirements for agricultural activities, such as the quantity of available land area, tools, types, and quantity of crops, and agriculture design of each district, including Building Covered Ratio, land alleviation, soil structure, and information about the total size of available space provided in each settlement from slum areas, urban agriculture cannot be implemented and will only fulfill report requirements for the government without any real impact to citizens. This will also lead to more disorganized agriculture activities that waste government funds without achieving the goal of ensuring food availability in Bandung.

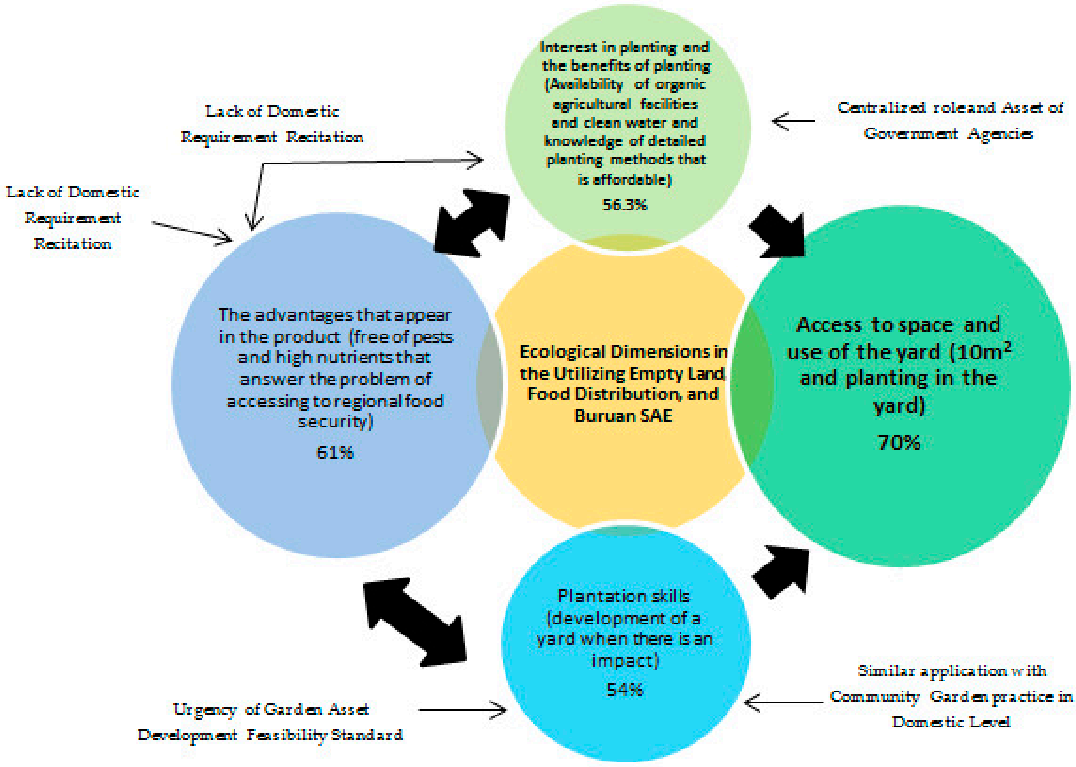

Figure 4. Components of the individual rift that affect the suitability of implementing the yard utilization program, harvest distribution, and stunting alleviation in the ecological dimension of Buruan SAE. The slices of each circle are influenced by the percentage at the main point.

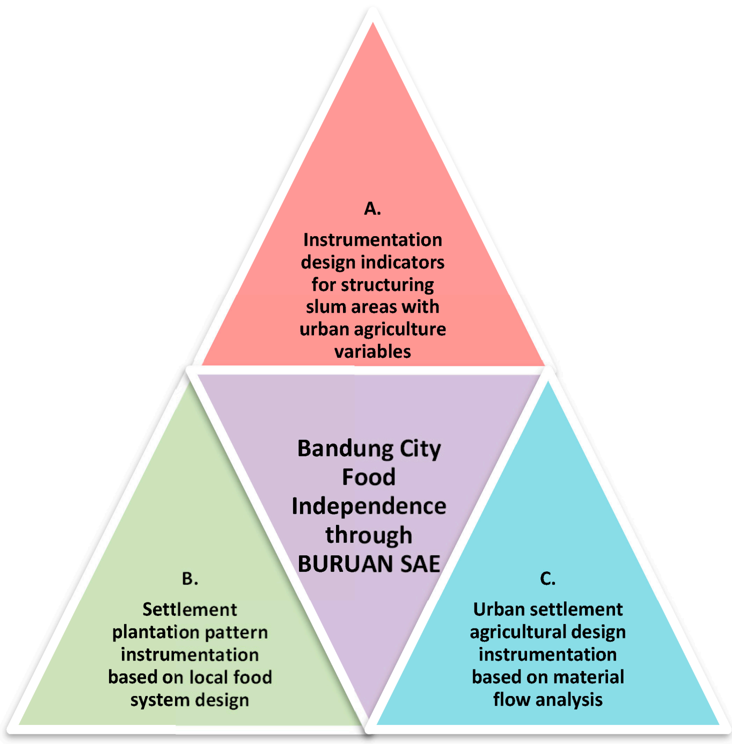

Figure 5. Results of social monitoring analysis on Buruan SAE policy instruments based on the individual rift within the framework of social metabolism.

5. Conclusions

The concept of the metabolic rift was used in this study to analyze the separation of urban low-income citizens from their food resources. It was also used to assess their social metabolism, especially in terms of relationships between the two variables. The consequences resulting from the growth of the business industry and services have a significant impact on low-income citizens in Bandung City, affecting their ability to access affordable food resources. The results indicated that the increasing popularity of Buruan SAE, due to various initiatives, such as citizens' hobbies and the impact of the COVID-19 pandemic, is insufficient to support the implementation of urban agriculture. This calls for the improvement of urban agriculture as a consistent and impactful food availability policy program. The lack of synergy in formulating a food availability policy, combined with the focus on procurement-oriented infrastructure in urban area development, hinders the effective implementation of urban agriculture. Consequently, individuals face reduced opportunities to engage in home agriculture.

Certain aspects related to the condition of residential settlements are not deemed urgent for the formulation of Buruan SAE policy due to their categorization as subsistence agriculture [2]. This classification eliminates the opportunity to analyze the production potential of each agriculture area to upgrade disorganized urban agriculture into a home-based agribusiness industry. Furthermore, policy should aim to increase participation from low-income citizens regarding agriculture activities, as their focus currently lies in acquiring agricultural techniques and meeting economic requirements to pursue an alternative livelihood. This orientation is expected to facilitate the formulation of a potentially exclusive and difficult-to-develop policy based on the concept of food availability.

In the practice of implementing Buruan SAE policy, it is crucial to incorporate a social monitoring-based design and identify the necessary material assets. Without these considerations, the policy may become centralized, focusing solely on implementing food distribution to the surrounding residents and relying heavily on government agencies, such as Urban Farmers Group. Social metabolism, as an aspect, shows that the perspective of urban society exploitation has not been significantly affected by the efforts of urbanization's renewal. These efforts are not considered a priority as they have no impact on the ability of urban agricultural farmers (low-income citizens) to understand the mechanism of the food market. This can be attributed to the lack of regional infrastructure development customized to the needs of urban agriculture.

This implies the need to view food availability as a superstructural achievement in overcoming the stagnation of urban agriculture caused by the lack of systemic policy support [47]. It aligns with the main objective of the local government to reconfigure the model of urban agriculture in response to the correlation between home agriculture and its implications for agricultural actors in households [46]. One of the inferences from this study is that the Buruan SAE program must align with the interest of farmers (low income citizens), who currently rely on the role of the GOBER agency. This emphasis will enable the local government to form a policy framework that implements new indicators for urban areas. Therefore, the local government should form a robust local food resilience system.

The analysis of the individual rift framework provided various insights that can support policy instruments in strengthening organized urban agricultural efforts for Bandung City Government. This is required to form a concrete implementation for agricultural activities practiced by low-income citizens in their respective homes, enabling a transition to a more centralized, top-down approach in the Buruan SAE program, which currently lacks specified impacts. Individual rift based on the concept of social metabolism can help both policymakers and various studies in analyzing the urban policy-making process by the government, which has limited information regarding various material requirements to implement urban agricultural programs. This limited knowledge serves as an obstacle to the active participation of low income citizens in the program.

Additionally, due to the priorities stemming from the impact of the COVID-19 pandemic and citizens' specific hobbies, the extent of participation in this agricultural program remains unclear since it can also be considered only as a thematic phenomenon that is temporal and unsustainable.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151310273/s1, Supplementary File S1.

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Article

Exploration of Coupling Effects in the Digital Economy and Eco-Economic System Resilience in Urban Areas: Case Study of the Beijing-Tianjin-Hebei Urban Agglomeration

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Abstract: Exploring the interaction and coupling effects within the digital economy and eco-economic system resilience in urban agglomeration areas is conducive to promoting high-quality sustainable urban development. Based on the coupling effect perspective, we construct a coupling coordination and development system with multiple elements, information, and interaction flow. The JJJ urban agglomeration from 2010 to 2019 was used as the study sample. The spatiotemporal differences and spatial effects of the coupled coordination were evaluated by combining the tools of combined weight model, coupled coordination model, nuclear density estimation, and exploratory spatial data analysis. The main results can be summarized as follows. (1) From 2010 to 2019, the digital economic index and eco-economic system resilience index of JJJ urban agglomeration maintained an upward trend, and the time series characteristics of the two sides showed a significant positive correlation. Additionally, the overall digital economic development index is better than the resilience development index of the urban eco-economic system. (2) In terms of the type of coupling coordination, the JJJ region has experienced a dynamic evolution process from the imbalance in 2010 to the primary coordination in 2019. The coupling and coordinated development levels of Beijing and Tianjin are obviously better than those of Hebei Province as a whole. (3) The coupling coordination of the system shows certain characteristics of spatial agglomeration and distribution. The overall spatial pattern presents a development pattern with Beijing and Tianjin as the core, and the gap between the north and the south is gradually narrowing. (4) Spatial spillovers and diffusion effects are evident. However, the influential factors have significant differences in the coupling and coordinated development between this region and neighboring regions. The results may provide theoretical support for the continuous improvement of ecological environment quality and green sustainable economic efficiency in urban agglomeration. It provides decision-making reference for promoting regional synergistic development strategy and optimizing spatial pattern of regional integration.

Keywords: digital economy; resilience of eco-economic system; coupling coordination; spatio-temporal evolution characteristics; spatial effect

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1. Introduction

1.1. Background

The report of the 19th CPC National Congress pointed out that China's economy has changed from the stage of rapid growth to the stage of high-quality development. In the context of entering the new stage of development and the "double carbon" target, the quality and sustainability of economic development is receiving increasing attention in China [1]. As a major carrier of economic, social, and environmental development, a variety of uncertain risks have become barriers to urban security and sustainable development, including natural disasters such as floods and earthquakes. The term also refers to terrorist attacks, political instability, ecological degradation, environmental pollution, lack of resources, and human-caused disasters that threaten the quality of the environment and human health. Therefore, cities with the carrier of human social development must constantly enhance their adaptability and resilience to resist these shocks to promote the healthy and orderly development of cities [2]. Research on the resilience of the urban eco-economic system will be of great importance for the sustainable and high-quality development of the economy and the enhancement of the performance of human ecological wellbeing [3,4]. Digital economics will gradually become a new engine of future economic growth, and the promotion of deep integration and coordinated development between the digital economy and the ecological environment will be the major theme of future development [5]. The digital economy as a new economic form will undoubtedly affect the economy, society, and the environment. Additionally, by virtue of its strong infiltrative attributes, it continues to broaden the scope and depth of integration with China's economic, social, scientific and technological, cultural, and other spheres of activity [6]. This will result in the transformation of China's economic development model through cloud computing, big data, artificial intelligence, and other frontier digital technologies. New economic conditions and green innovative development patterns have been brought into being, bringing great opportunities for China's urban construction and high-quality economic development [7,8]. Under this background, it will play an important role in the implementation of China's high-quality sustainable development strategy to study the coupling and coordination relationship between urban digital economy and eco-economic system, as well as to clarify the internal coupling and coordination rules and mechanisms between them.

Under the impetus of the new normal and the new urbanization development strategy, urban agglomeration has become an important supporting structure of China's economic and social development [9]. The Beijing-Tianjin-Hebei (the abbreviation JJJ, the same as below) urban agglomeration is the largest urban agglomeration in north China, with a land area of 216,800 square kilometres (2.3 percent of the country's land area) and a population of 113 million people (eight per cent of the country's total population) in the region. As of 2019, it accounts for nine per cent of China's GDP. It is one of China's fastest growing, most open, and innovative urban agglomerations. It has become an important driving force in sustaining China's participation in the global market, but it is also prone to environmental constraints and resource issues [10–12].

The digital and ecological economies are the most important topics in the current economic and environmental policy agenda [13,14]. The ecological economy provides the opportunity for transformation [15], and the digital economy is the new engine and driving force for achieving economic growth and social change [16,17]. Undoubtedly, the two are highly related. However, most of the current academics are carrying out research on both independently. Their studies include research into the digital economy, mainly focusing on promoting carbon emission reduction [18,19], digital finance [20], risk management [21], sharing economy development [22,23], promoting high-quality and resilient economic development [24–27], promoting industrial structure upgrading [28], and circular economy development content [29,30]. The eco-economy is mainly concerned with improving resource efficiency [31,32], green technology innovation [33], industrial eco-economy [34], and reconciling environmental and economic sustainability [35–37]. Only a few institutions and scholars have started to reflect on the compatibility of the digital economy ecosystem with the carbon footprint and the transformation of the green and ecological economic system [38–40]. At present, our country is in the process of constructing a new development pattern of "double cycle", exploring the high-quality integration of ecological economy and digital economy, and building a sustainable digital age. This is an inevitable requirement to implement the new development concept, realize the organic unity of "economic, social and ecological effects", and an important strategic decision to realize the international commitment of "30.60" [29].

The innovation of this research may be mainly reflected in the following points: first, based on value creation and urban resilience development perspective, it is important to investigate the transmission mechanism, dynamic evolution, and spatio-temporal differentiation characteristics of the regional digital economy and the resilience of eco-economic system. The second objective is to incorporate spatial effects into the research framework in order to explore the spatial heterogeneity of coupling and coordination between the two in the urban agglomeration of JJJ. Thirdly, in order to enhance the level of coupling and coordination between the two and to promote the balanced and synergistic development of the JJJ cluster of cities, after refining the search units, we take the 13 prefecture-level cities in the JJJ cluster of cities as our search objects. This is performed to better explore the spatiotemporal differences and spatial effects of their coupled and coordinated development.

1.2. Literature Review

Digitization and sustainable development are the main trends of economic and social development [41–43]. By harnessing the power of the internet and inclusive finance to bring technological innovation effects and resource allocation effects into play, the digital economy enhances the rational sharing and equitable distribution of the wellbeing outcomes of economic development [44–48]. The scale, technology, and structural effects of digital economy development are amplified in terms of their impact on the resource environment [7,49–55]. The digital economy reduces ecological pollution through the green development effect and innovation development effect, which in turn promotes eco-economic efficiency [56–58].

The connotation, measurement methods, theoretical studies, and empirical studies on the resilience of urban eco-economic systems have also been enriched by scholars [59]. In terms of connotation and definition, some scholars have proposed four dimensions of urban economic resilience, namely, resilience, recovery, reorganization, and renewal [60], but most scholars define it as the ability of cities to achieve economic recovery and to create new economic development paths through reconfiguration after effectively coping with external disturbance shocks [61]. At present, there is not a uniform method for measurement. According to the focus of the study, various methods have been designed, including the single-core variable method, the composite index method, the toughness maturity model, the social network model, and the scenario analysis method [62]. At the research scale, it involves counties, municipalities, and specific regions [63]. In terms of theoretical perspectives, scholars mainly sorted out urban adaptive governance, climate change, sustainable management of natural resources, disaster prevention, and urban resilience, which laid the foundation for in-depth research on urban resilience [64]. The empirical research is mainly formulated from the perspectives of urban system resilience operating mechanism, effectiveness evaluation, design planning, and other dimensions [65]. It is important to discuss the influence mechanism and action mechanism on urban eco-economic development based on industrial structure, industrial agglomeration, economic density, entrepreneurial vigor, social security, etc. [66].

1.3. Problem Statement and Objectives

In summary, firstly, the scale of research is concentrated in the country, provinces and other macro categories, and there is a paucity of research on the micro and meso level, such as urban agglomeration. The second problem is the lack of related research on the law of two-way interactions, the dynamical evolution of the degree of interrelated coupling coordination, and the characteristics of spatiotemporal differentiation. Thus, these considerations are based on consideration of regional representativeness and regional economic impacts. In this paper, we focus on the exploratory dynamic analysis of the index coupling coordination relationship and the spatio-temporal evolution pattern of the digital economy and the resilience of urban eco-economic systems. Additionally, these processes reveal their developmental features and the law of coordination of coupling.

Given this, after combing through a large body of studies, the interaction mechanism between infrastructure, structural optimization, technological innovation, and the resource allocation effect of the digital economy and resilient eco-system development forms the basis of this study. Motivated by the combination weight assessment model, the degree of coupling model, kernel density analysis, and the spatial econometric model, the goals of our paper are to address the following questions:

(1) Overall, what is the time series change and the evolution of the spatiotemporal pattern of resilient coupling and coordinated development of digital economy and eco-economic system resilience in JJJ urban agglomeration?
(2) What is the distribution law of spatial agglomeration, and what is the evolutionary trend of their coupling and coordinated development?
(3) Are there any spatial spillover effects, and what are the influencing factors of both?
(4) Given the above findings, how can differentiated policy recommendations for high quality digital economy development and eco-system resilience be advanced?

The purpose of this paper is to provide a reference for the relevant decisions on the coupling and coordinated development of digital economy and resilience of eco-economic system in China and other countries or regions with similar conditions. The results of the study will help to overcome the contradiction between economic development and ecological environment. Additionally, these results will simultaneously increase people's wellbeing in the coordinated development process. Promoting high quality economic and social development and forming a new development model are very important.

2. Research and Design

2.1. Theoretical Framework

As a facilitator of high-quality economic development, the digital economy provides new technical conditions and a social environment for resilient construction and development of urban eco-systems through digital technologies [67,68]. This improves the total green factor productivity of the socioeconomic system by reducing information asymmetry and optimizing the efficiency of resource allocation [30,69,70], thereby improving the level of resilience of the urban eco-economic system. Consequently, enhancing the resilience of urban eco-economic systems will also feed back into the field of digital economy development. This will boost the solid development of the digital economy in cities and create environmental policies and economic foundations for digital economy development [71]. Specifically, the digital economy improves the matching accuracy of resources, energy efficiency, information symmetry among market players, information communication efficiency, and overcomes the disadvantages of market failure by virtue of its highly permeable properties. It is important to improve the operation and supply efficiency of the economic system and strengthen the endogenous drive of economic development. The digital economy can enhance the ecological efficiency of cities by building a feedback mechanism of ecological protection and propagating the positive concept of green living [72]. The digital economy enhances the informationization and intelligentized level of cities through technology embedding. These promote the transformation and upgrading of urban industrial structure and rapidly accumulate a large number of innovative resources [30]. This deep integration of the digital economy and the real economy allows for the reconstruction of the value creation model, developing a new industrial ecology, as well as promoting the advancement of green technology in China's "three-high" industries. On the other hand, building and developing the resilience of urban eco-economic systems provides new opportunities for development and economic foundations for the digital economy [73,74]. The development and construction of new infrastructure, smart cities, and other major urban strategic projects align with the digital economy, which results in the deep integration of digital economy development and the resilience building of urban eco-economic systems. This results in interacting with one another to achieve synergy and giving full play to the multiplier effect and the value co-creation effect between one another [75]. Figure 1 illustrates the mechanism of the role of coupling and co-ordinate development.

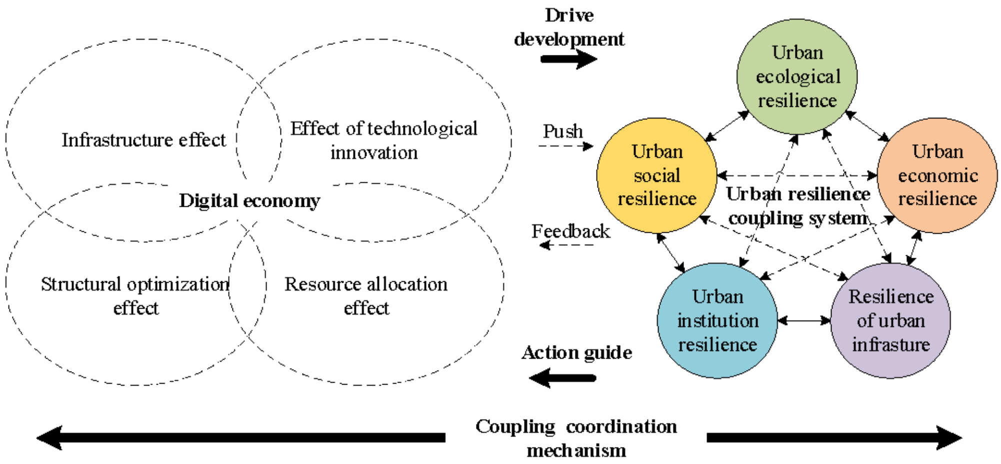

Figure 1. Synergistic Mechanism of the Digital Economy and the Resilient Development of the Urban Eco-economic system.

2.2. Study Area

According to the outline of Beijing-Tianjin-Hebei Cooperative Development Plan (2015.04), the planning area includes two municipalities directly under the central government of Beijing and Tianjin and 11 prefecture-level cities in Hebei Province, forming a spatial layout pattern of 11 + 2 [76]. It is an important part of the Bohai region, plays an important role in the economic development of the Bohai region, and plays an important strategic role in national development [77]. Therefore, this paper takes the Beijing-Tianjin-Hebei (the abbreviation JJJ) urban agglomeration as the research object. Figure 2 is a graph of vector map data for the JJJ urban agglomeration (http://ngcc.sbsm.gov.cn, accessed on 10 January 2022).

2.3. Research Methods

In this study, an evaluation system was constructed for the coupling and coordinated development of the digital economy and eco-system resilience (Figure 3). The framework consists of three stages: (1) quantifying the assessment of resilience development of digital economy and eco-economic system and analyzing their related data according to the measurement results, including evaluation index, coupling degree, and coupling coordination degree. (2) The next step is visualization of a non-equilibrium spatial analysis of the coupling and coordinated development of the regional digital economy and eco-economic system resilience, including kernel density estimation, the spatiotemporal transition characteristics of their degree of coupling coordination, and spatial correlation. (3) The selection of possible driving factors for both coupling and coordinated development, and the determination of the spatial landmark regression model, are important. Additionally, one should perform a spatial analysis of the spillover effect.

2.3.1. Evaluation Model Based on Combinatorial Weights

In order to determine the weight, it is necessary to choose the corresponding weighting method, and the weight determined by different weighting methods is not the same. The combination of subjective and objective weighting is a method of weighting between subjective and objective values. Weight determination has both subjective qualitative components and quantitative computation of the data [78]. In an effort to reduce the influence of subjective factors and fully explore the original data, to weight the evaluation index, we use the subjective and objective combination weighting method that combines AHP and entropy.

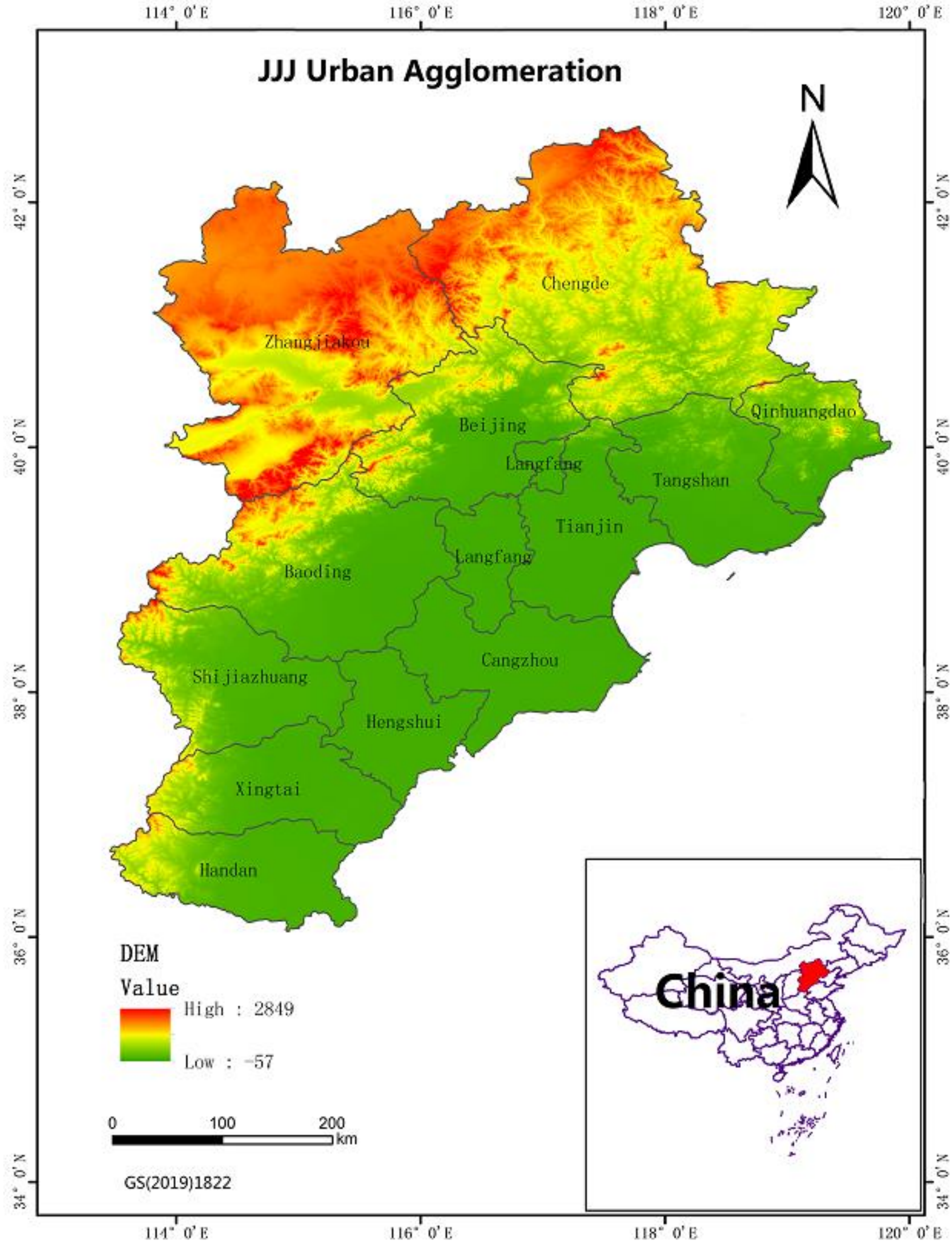

Figure 2. JJJ urban agglomeration in China.

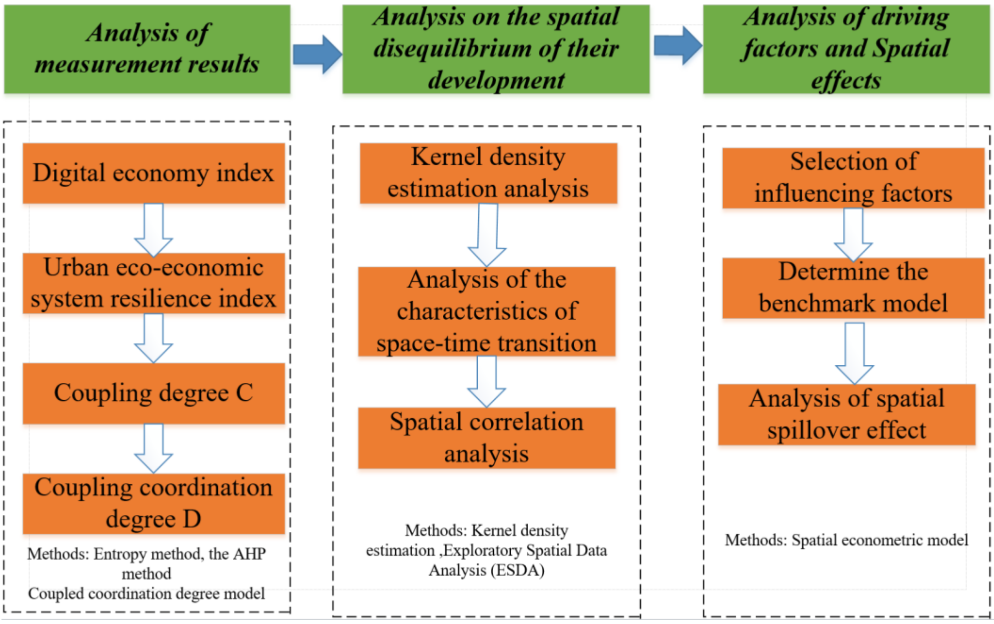

Figure 3. The research framework.

Analytic hierarchy process (AHP) is a hierarchical weight decision analysis method put forward by American operations researcher T.L. Saaty [79]. This method combines quantitative analysis with qualitative analysis to solve multi-objective complex problems. With the advantages of its flexible and concise system, it has been widely valued and applied in all fields of social economy, such as engineering planning, resource allocation, programme sequencing, policy development, performance evaluation, energy systems analysis, marine systems analysis, and urban planning [80–84].

This method uses the experience of decision makers to judge the relative importance of the criteria for measuring whether the goals can be achieved or not, and it reasonably gives the weight of each decision-making scheme. The rules for defining the scale of the judgment matrix are as follows: compared with the two factors, if they have the same importance, the scale is 1; when the current one is slightly more important than the latter, the scale is 3; when the former is obviously more important than the latter, the scale is 5; when the former is stronger more important than the latter, the scale is 7; when the former is most important in relation to the latter, the scale is 9, and the scales of 2, 6, and 8 represent the intermediate value in the above judgment.

Specific methods include: 50 experts are asked to assign the index using the 1 to 9 scale method, and then this is applied to computing the scaled mapping value of the entropy enhanced method. Once the judgment matrix is established, the weight of the index is computed according to the root method. Finally, a one-tailed test was performed.

(1) Once the initial index data are normalized by the range method, the difference coefficients for each index are calculated by the ordinary entropy method.

$$g_j = 1 - \frac{1}{ln\ m}\sum_{i=1}^{m} p_{ij}\ ln\ p_{ij},\ p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{1}$$

(2) The AHP weighting method is used to calculate the scale mapping value of 1 to 9 in the improved entropy method.

First of all, find the maximum difference coefficient ratio D:

$$D = \frac{max g_j}{\min g_j} \tag{2}$$

Secondly, find the mapping ratio R of 1–9 scale:

$$R = \sqrt[a-1]{\frac{D}{a}} \quad (3)$$

Finally, the mapping value of the 1–9 scale is calculated.

(3) The mapping value of 1–9 scale is obtained by multiplying the original scale value of R by 1–9 scale in AHP weighting method, and the result is shown in Table 1. Of these, 0–8 corresponds to a subtraction of 1 on a scale of 1–9 in the AHP method.
(4) Construct the judgment matrix of the improved entropy method and calculate the weight.

Table 1. The corresponding relationship between scale and mapping value.

Scale	1	2	3	4	5	6	7	8	9
Mapping value	$1 \times R^0$	$2 \times R^1$	$3 \times R^2$	$4 \times R^3$	$5 \times R^4$	$6 \times R^5$	$7 \times R^6$	$8 \times R^7$	$9 \times R^8$

Calculate the difference coefficient ratio of the index $r_{jk} = \frac{g_j}{g_k}(g_j > g_k)$. The difference between the improved entropy method and the one with the smallest difference of the mapping value of the 1–9 scale is the result of comparing the relative importance of the two indexes, so as to construct the judgment matrix.

(5) Calculate the weight value and evaluation value of the index.

According to the judgment matrix, the eigenvector corresponding to the maximum eigenvalue of the matrix is solved and normalized, and thus the weight is obtained. Finally, the evaluation value of each index can be obtained.

2.3.2. Nuclear Density Analysis

Kernel density estimation is a nonparametric testing method. In comparison to other estimation methods, this method does not use prior knowledge of data distribution and does not attach any assumptions to data distribution. Given its weak model dependence and excellent statistical properties, this method has been used extensively in the exploration of the spatial distribution imbalance problem [85].

The formula is as follows:

$$\begin{aligned} f_n(x) &= \frac{1}{nh_n}\sum_{i=1}^{n} K\left(\frac{x_i - x^-}{h_n}\right) \\ K(x) &= \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{x^2}{2}\right) \end{aligned} \quad (4)$$

In the form, $f_n(x)$ is a for probability density function; $K(x)$ is a for Gaussian kernel density function; n represent number of samples; h_n represent broadband; and x^- is the mean value. In general, the wider the broadband, the smoother the density function and the lower the estimated precision.

2.3.3. Coupled Coordination Degree Model

The calculation model of the coupling and coordinated development of regional digital economy and urban eco-economic system resilience is as follows [86]:

$$C = 2\{(U_1 * U_2)/[(U_1 + U_2)(U_1 + U_2)]\}^{1/2} \quad (5)$$

where: the coupling degree value $C \in [0,1]$, and, the larger the C value, the higher the level of resonance coupling between the two systems, and vice versa.

The coupling degree reflects the similarity level of the system elements and does not represent the overall level of factor development and the synergistic effect of the two. It cannot well characterize the regional digital economy and the level of resilient urban eco-economic system development and its coordination or further construct the coupling coordination degree model. The formula is as follows:

$$D = (C * T)^{1/2},\ T = \alpha U_1 + \beta U_2 \quad (6)$$

where: D it is the coupling coordination degree; T it is the comprehensive coordination index of the digital economy and the urban eco-economic system resilience; α and β are the degree of contribution of the digital economy and the urban eco-economic system resilience development to the economy and society, respectively. Considering that the contribution degree of the two is not distinguished from each other [81], here, take $\alpha = \beta = 0.5$. According to D, the size of coupling coordination rrefers to previous research [87,88]. Establish the grade evaluation standard of coupling coordination degree, as shown in Table 2.

Table 2. Grade evaluation criteria of coupling coordination degree.

Coupling Coordination Degree	Coupling Coordination Level	Coupling Coordination Degree	Coupling Coordination Level
$0 < D \leq 0.2$	Severe disorder	$0.4 < D \leq 0.6$	Primary coordination
$0.2 < D \leq 0.3$	Mild disorder	$0.6 < D \leq 0.8$	Middle coordination
$0.3 < D \leq 0.4$	Barely coordinate	$0.8 < D \leq 1$	Senior coordination

2.3.4. Exploratory Spatial Data Analysis (ESDA)

(1) Global autocorrelation analysis

The global spatial autocorrelation analysis method is used to identify the spatial agglomeration of digital economy and urban eco-economic system resilience development level in the JJJ.

$$I = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i - x^-\right)\left(x_j - x^-\right) / \left\{\sum_{i=1}^{n}\left(x_i - x^-\right)^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right\} \quad (7)$$

where n is the number of spatial units in the study area; x_i and x_j represent the coupled coordination index of cities I and city j; x^- represents the average of the study object; w_{ij} is the adjacent spatial weights matrix. $I \in [-1,1]$, and, if $I > 0$, this indicates that the degree of coupling and coordination of the digital economy and the urban eco-economic system resilience index in the JJJ region is spatially clustered and has a positive spatial correlation.

(2) Local autocorrelation analysis

The local Moran's I index is usually used to measure and draw the LISA aggregation map to measure the spatial correlation characteristics between this region and adjacent regions, including HH, LL, HL, and LH [89]. The calculation formula is as follows:

$$I = \left(x_i - x^-\right)\sum_{j=1}^{n} w_{ij}\left(x_j - x^-\right)^2 / \sum_{i=1}^{n}\left(x_i - x^-\right)^2 \quad (8)$$

In the form, x_i, x_j, and w_{ij} are related to the definition of symbols, which is the same as (7); I is a local Moran's I index, with a range of values $[-1, 1]$, and a positive value indicates the spatial agglomeration of similarity around the regional unit.

2.3.5. Spatial Econometric Model

Due to the existence of technical diffusion and spillover effects in the region, spatial factors need to be considered [90]. The commonly used models include (SEM), (SAR), and (SDM) in the following forms:

(1) Spatial Error Model (SEM)

$$\begin{array}{c}\gamma = \beta_i x_i + \mu_i + \eta_i + \phi_{i,t} \\ \phi_{i,t} = \lambda \omega \phi_{i,t} + \varepsilon_{i,t}\end{array} \quad (9)$$

where: ω represents the adjacent spatial weights matrix; μ_i and η_i represent the individual and time fixed effects, respectively; x_i represents explanatory variables; $\varepsilon_{i,t}$ represents the random interference term; and λ represents the error spatial correlation coefficient.

(2) Spatial lag model (SAR)

$$\gamma = \rho \omega \gamma_{i,t} + \beta_i x_i + \mu_i + \eta_i + \varepsilon_{i,t} \quad (10)$$

where: ρ represents the coefficient of the spatial hysteresis term.

(3) Spatial Durbin Model (SDM)

$$\gamma = \rho \omega \gamma_{i,t} + \omega x_{i,t} \beta + \mu_i + \eta_i + \phi_{i,t} \quad (11)$$

where: β indicates the spatial autoregressive coefficient of the explanatory variable, and the meaning of other variables is unchanged.

(4) Build spatial weight matrix

Construct adjacency matrix (W), inverse distance matrix (D), and economic distance matrix (E) to test the robustness of spatial metrology results. If the city of i and the city of j are adjacent $W_{ij} = 1$, the other takes 0; considering that the spatial effect L_{ij} decays with the increase in distance, an inverse distance matrix, based on the square reciprocal, is established, and, if i $\neq$ j, the $D_{ij} = \frac{1}{L_{ij}^2}$, other takes 0; the economic weight matrix is constructed using GDP per capita, and, if i $\neq$ j, the weight is taken as $E_{ij} = \frac{1}{|g_i - g_j|}$, and the other is 0.

2.4. Indicator Selection and Data Sources

Combined with the analysis of coupling coordination mechanism (Figure 1) and related research results in [31–40], this paper decomposes the urban eco-economic system resilience index into five dimensions: economic level resilience, social level resilience, institutional resilience, infrastructure resilience, and ecological environment resilience, and it constructs 21 evaluation indicators to measure them. Among them, urban economic level is the basis and driving force of urban resilience regulation and control [15], which directly affects urban ecological, environmental, and social levels, mainly including urban economic structure, urban economic efficiency, and urban economic innovation capacity, etc. The urban social level is the guarantee of urban resilience and sustainable development [36]. We enhance the resilience of urban social development by providing labor for urban economic development, technical support for enterprise development, and solutions for resource utilization and environmental management. Urban institutional factors are an important guarantee for strengthening urban resilience and help break down various barriers between urban resources (people, money, materials, information, processes, etc.) so that resources are rationally allocated and information is effectively communicated between various urban sectors [39]. Infrastructure is the artificial environment of the city, which is a key factor in ensuring the resilience of human and urban environmental systems [91], similar to the "meridian skeleton" of the body, and it plays an important role in ensuring sustainable urban development [61]. The ecological environment is the spatial carrier of sustainable urban development, mainly including the regional natural environment and urban landscape green space, which can provide various ecosystem services based on natural ecological processes to enhance the ecological resilience of cities [92].

On the basis of the mechanism analysis and previous research findings [18–24], in this study, we intend to measure the level of development of the digital economy from four levels: digital infrastructure, digital industry development, capacity for digital innovation, and digital financial inclusion. Digital infrastructure is the guarantee, and this study is mainly concerned with broadband internet infrastructure and mobile internet infrastructure, which are two indicators to measure. They were characterized by the number of internet users per 10,000 people and the number of mobile phone users per 10,000 people, respectively. Digital industry development is the core of digital economy development, and this study mainly measures the development of e-commerce industry, the foundation of information industry and the output of telecommunication industry. They were characterized by the number of urban e-commerce parks, the number of employees in the information transmission, computer services and software industries, and the total number of telecommunications services. Digital innovation ability is the key to the development of digital economy. This research mainly measures digital innovation from the support of digital innovation elements, digital innovation output level, and digital high-tech penetration. It is characterized by the expenditure of science and technology, the number of patents related to the digital economy per 10,000 people, and the penetration of digital high-tech applications in listed companies. Finance is the hub of resource allocation and an important driving force for the development of the real economy. Digital inclusion finance is an essential component of digital life, which is measured in part by the breadth of coverage, depth of use, and digitization of digital inclusion finance.

Lastly, multiple collinearities may exist among the index variables chosen in this study. For this reason, prior to the empirical analysis, this study uses the variance expansion factor (VIF) to analyze whether multicollinearity exists in all of the index variables. This shows that the VIF for each index variable is less than 10, i.e., there is no problem of multicollinearity between the variables. As shown in Table 3.

The research data come from the statistical bulletins of official websites, such as the China Statistical Yearbook, the China Science and Technology Statistical Yearbook, and the China Environmental Statistical Yearbook and the Statistical Yearbooks of Beijing, Tianjin and Hebei Province from 2011 to 2020. The missing data of individual years are supplemented by linear interpolation, and the macro variables are adjusted for the base period of 2010. The distribution data of e-commerce parks come from the e-commerce industrial park development alliance (http://cyylm.ec.com.cn/, accessed on 10 January 2022), and the patents related to digital economy come from the patent search website of the State intellectual property Office (http://pss-system.cnipa.gov, accessed on 10 January 2022), the penetration degree of digital high-tech applications in listed companies [①] comes from the China Digital economy Research Database (https://cn.gtadata.com/, accessed on 10 January 2022) provided by CSMAR, and the digital inclusive financial data comes from the China Digital inclusive Financial Index (https://tech.antfin.com/research/data, accessed on 10 January 2022), measured by the Digital Finance Research Center of Peking University and Ant Financial Services Group. ([①] The penetration level of high technology is mainly reflected by calculating the frequency of artificial intelligence technology, blockchain technology, cloud computing technology, and big data technology. The digital technology application in the listed companies reports the frequency of the breakdown of indicators, and then the average aggregation to the city scale is used to reflect the penetration level of new and high technology).

Table 3. Evaluation index system.

Target Layer	Criterion Layer	Indicators	Indicial Attribute	VIF
Resilience of eco-economic system	Economic level resilience	Per capita GDP	(+)	3.174
		Per capita fiscal expenditure	(+)	2.546
		FDI investment amount	(+)	1.749
		Year-end savings balance of urban and rural residents	(+)	1.538
		Per capita investment in fixed assets	(+)	2.107
		The proportion of the output value of the tertiary industry in GDP	(+)	4.312
	Social and institutional resilience	Social security accounts for the proportion of financial expenditure	(+)	3.114
		Urban per capita disposable income	(+)	1.472
		Number of health workers per thousand people	(+)	2.384
		Number of persons receiving higher education per thousand people	(+)	1.067
		Proportion of unemployed population	(−)	3.469
		Density of urban health stations	(+)	2.463
		Proportion of personnel of public management and social organizations	(+)	4.382
		Density of government agencies	(+)	2.573
		Urban governance capacity	(+)	4.623
		Aging rate	(+)	3.267
	Infrastructure resilience	Per capita urban road area	(+)	2.134
	Eco-environmental resilience	Length of urban drainage pipeline	(+)	1.743
		Urban per capita electricity consumption	(+)	2.864
		Number of urban communication base stations	(+)	3.428
		Degree of material supply guarantee	(+)	4.372
		Perfection of disaster prevention and mitigation facilities	(+)	5.143
		Per capita public health facilities	(+)	3.486
		Green coverage rate in built-up area	(+)	6.417
		Per capita green space area	(+)	5.439
		Discharge of industrial wastes	(−)	7.642
		Harmless treatment rate of municipal solid waste	(+)	3.734
		Air quality index	(−)	4.865
		Number of Internet users per 10,000 people	(+)	1.903
Digital economy	Digital infrastructure	Number of mobile phone users per 10,000 people	(+)	2.197
		Number of urban e-commerce parks	(+)	1.172
	Digital industry	Number of employees in information transmission, computer services and software industry	(+)	3.476
		Total amount of telecom service	(+)	2.839
		Proportion of expenditure on science and technology	(+)	3.765
	Digital innovation ability	Number of patents related to digital economy per 10,000 people	(+)	5.467
		Penetration of digital high-tech applications in listed companies	(+)	6.728
		Digital inclusive financial coverage breadth index	(+)	2.034
	Digital inclusive finance	Digital inclusive Financial use depth Index	(+)	2.128
		Digital inclusive Finance digitalization Index	(+)	3.875

3. Result Analysis

3.1. Analysis of Measurement Results

According to the above methods and the comprehensive evaluation index system, the resilience index, coupling degree, and coordination degree of digital economy and urban eco-economic system in Beijing, Tianjin and Hebei Province from 2010 to 2019 are calculated (Figure 4).

(1) From Figure 4, it can be seen that: during 2010–2019, the level of digital economy and the urban resilience assessment index in the JJJ region as a whole exhibited a wavy upward trend, and time series features from both sides showed significant positive correlation. Additionally, the global index of digital economic development is better than the index of urban resilient development. In particular, it is divided into stages: high-velocity growth stage I (2010–2015) and medium-high-velocity growth stage II (2016–2019). The average values of the digital economic development index and the urban resilience development index are low, and the rate of growth is relatively rapid in the first stage. From 2010 to 2015, the growth rates of the digital economic index were 20%, 22.22%, 23.64%, 5.15%, and 11.89%, respectively. The resilient urban development index has a growth rate of 22.73%, 3.71%, 35.71%, 26.32%, and 33.33%, respectively, among others. Secondly, the rate of growth of both the digital economic development index and the urban resilient development index obviously slowed after 2016. Between 2015 and 2019, the growth rate of the digital economic index was 9.84%, 1.49%, and 5.82%, respectively, in the country. The urban resilience development index had growth rates of 26.44%, 17.27%, and 7.75%. Overall, the assessment index of digital economy and resilient urban development in the JJJ region is not perfect, and much progress remains to be made in achieving the coordinated development of the regional digital economy and urban resilience.

(2) In the JJJ region, the degree of coupling coordination of the digital economy and the resilient urban development index showed a consistent upward trend overall, especially after 2015. From 2015 to 2019, the growth rate of coupling coordination degree was 12.30%, 8.15%, 4.68%, and 3.22%, respectively. Beijing, Tianjin, and Hebei showed similar time-series evolution rules across the entire development process. This study demonstrates that the interplay between digital economy and resilient urban development in JJJ is continually reinforced, and the degree of internal co-ordination between the two systems is progressively improved. Additionally, with their own attributes of high permeability and the deep integration of major issues in urban governance, construction, and development, they mutually promote each other and the tendency towards development is evident.

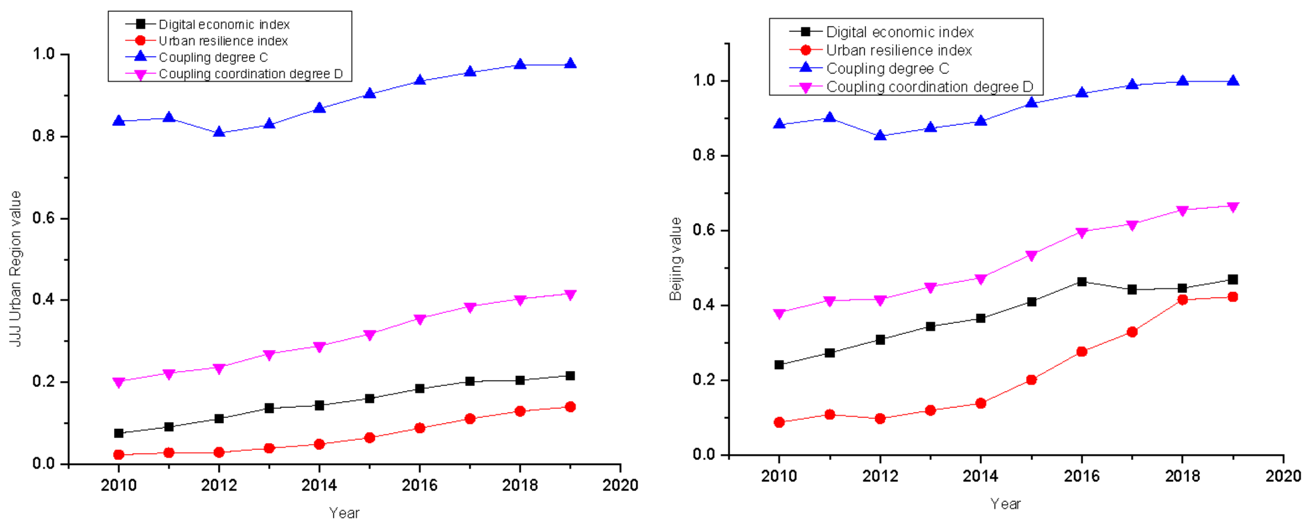

Figure 4. *Cont.*

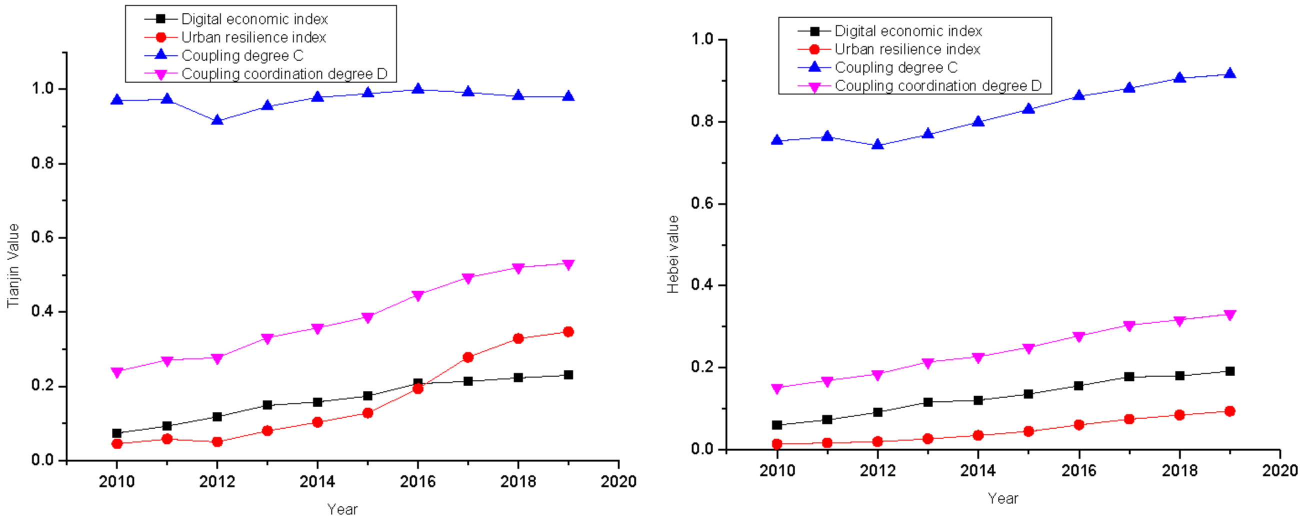

Figure 4. Change trend of digital economy and urban resilience index, coupling degree and coordination degree in JJJ region from 2010 to 2019.

The process of developing and evolving the degree of coupling coordination can be divided into three stages. The first phase, from 2010 to 2014, lies between 0.201–0.288, which is at the slightly disequilibrium stage, indicating that there is little interaction between digital economy development and resilient urban development. At the same time, due to the low level of resilience development of urban eco-economic system, it is unable to provide the necessary environmental planning and industrial policies for the development of the digital economy. Both lack effective support and promotion. During the second phase, from 2015 to 2017, the JJJ region is in between 0.317–0.385, which indicates that the development of digital economy and urban resilience in the JJJ region is still in a state of flux. Matching the two sides in planning the digital economic environment and building industrial policy, the technical conditions for building urban resilience and the social development environment must be strengthened. During the third phase, from 2018 to 2019, the JJJ region lies between 0.403–0.416, which is in the primary coordination stage, indicating that the benign coupling and coordinated developmental situation that they favor one another was initially formed.

3.2. Analysis on the Spatial Disequilibrium of Their Development

3.2.1. Kernel Density Estimation Analysis

Because of differences in factor endowments and stages of development in different regions, it is possible that the measurement results and their respective trends with the passage of time are different. For this reason, in this paper, the kernel density estimation method of nonparametric estimation is used to analyze the differences in the dynamic evolution of digital economy and eco-economic system resilience assessment index and the degree of urban agglomeration coordination JJJ from the perspectives of distribution location, distribution shape, and distribution scalability.

Following the method of Gaussian kernel density estimation, Matlab software (MatlabR2022a) is used for kernel density estimation (see Figures 5–7). The results show that, over the period 2010–2019, the core density curve shifted to the right, and the peak continued to decrease, showing a trend from "peak" to "flattening." The curve shape softened, indicating that the development gap between cities in JJJ region gradually widened, and the convergence between cities decreased. Among them, the core density curve of digital economic evaluation index has the tendency to evolve to double peak, presenting the "M" double peak distribution. It shows that the development of digital economy in JJJ urban agglomeration is polarized, and there are obvious differences between regions. The core density curve of the resilience index of urban eco-economic system shows the evolution from "Twin Peaks Club" to "Multi-Peaks Club". It shows that there are multipolarity and multilevel development trends. Additionally, with the passage of time, its peak is also more and more flat, and the toughness of the high-value area is gradually highlighted. The nuclear density curve of the coupling coordination degree keeps shifting to the right, the peak value keeps decreasing, the shape of the curve becomes moderate, and there is an evolution of the "bimodal club" to the "multi-modal club", showing a polycentric development pattern. It shows that, over time, cities at the lower coordination stage and below gradually move to the middle and upper coordination stage. However, the coupling coordination gap of different regions has been enlarged because of the different speed and scale of the migration. In the future, it is urgent to optimize and coordinate the development of the digital economy and the resilience of urban eco-economic system so as to achieve balanced and sustainable development in the region.

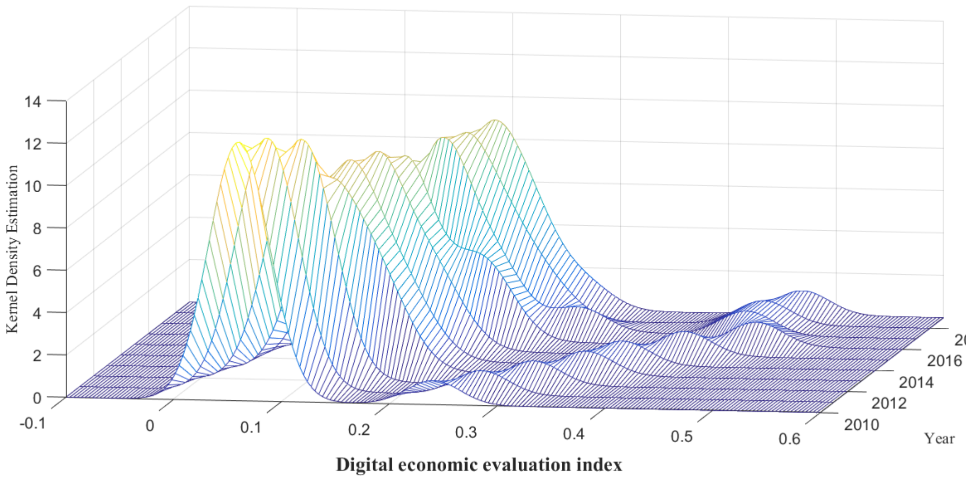

Figure 5. Core density map of digital economic evaluation index of JJJ urban agglomeration from 2010 to 2019.

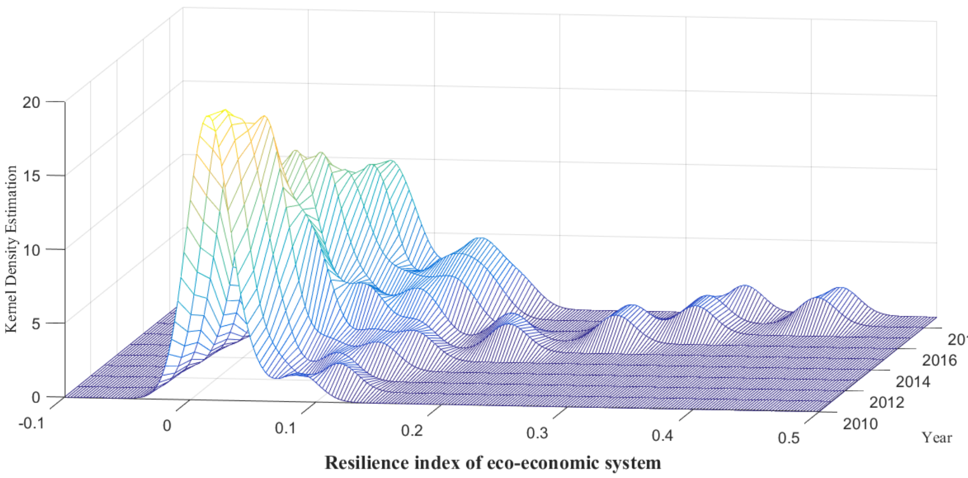

Figure 6. Core density map of eco-economic system resilience (evaluation index of JJJ urban agglomeration from 2010 to 2019).

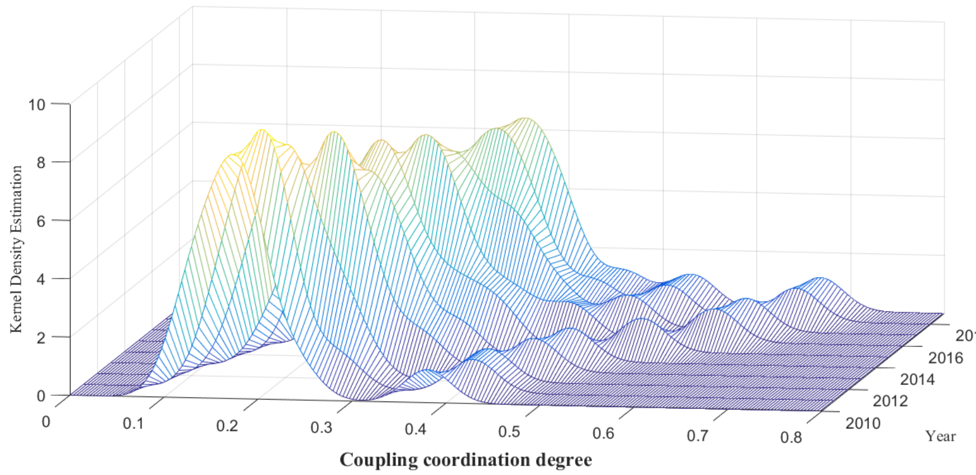

Figure 7. Nuclear density map of coupling coordination degree between JJJ urban agglomeration from 2010 to 2019.

3.2.2. Analysis of the Characteristics of Space-Time Transition

To further analyze the trend of dynamic spatial evolution of the degree of coupling coordination of the digital economy and the urban eco-economic system of 13 cities in the JJJ region, we used the natural segment method to dynamically visualize the degree of coupling coordination of the two developmental indices in the JJJ region in 2010, 2013, 2016, and 2019. Depending on the value of the degree of coupling coordination, it is drawn by the Arc-Gis10.2 software. (Figure 8).

According to Figure 8, overall, the coupling degree of digital economy index and resilience index of urban eco-economic system shows a certain spatial agglomeration distribution in space, and it shows an increasing trend and spatio-temporal pattern. Additionally, with the passage of time, it presents the characteristics of the distribution with Beijing and Tianjin as the nucleus, and there are large differences between different cities. Here, we perform a stepwise analysis, starting from the temporal and spatial dimensions.

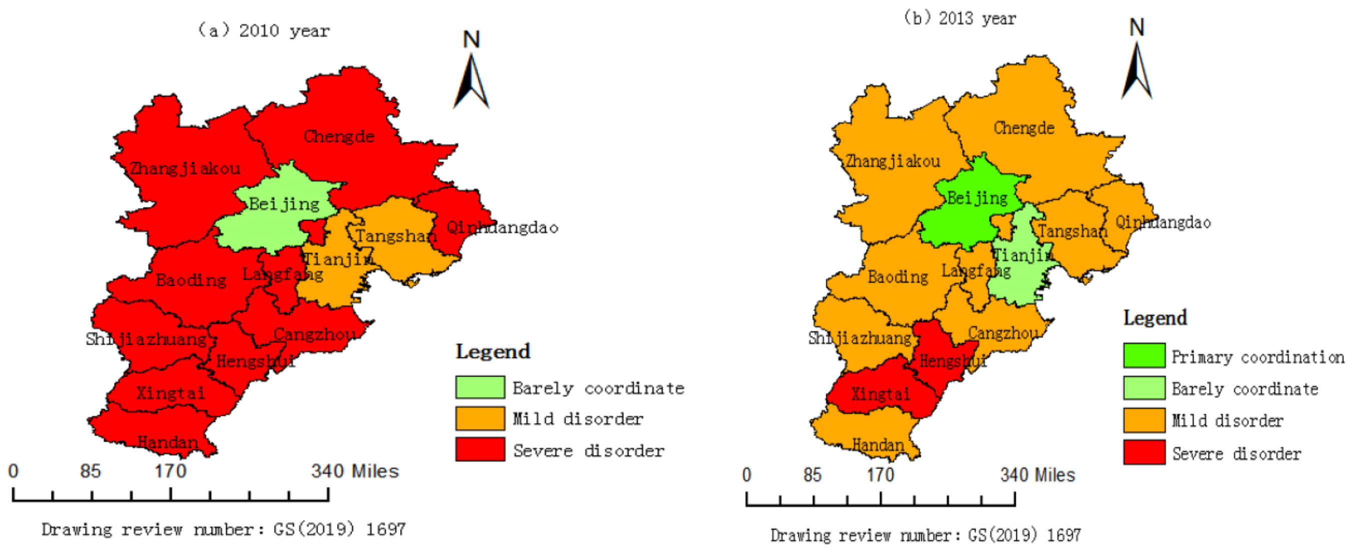

Figure 8. *Cont.*

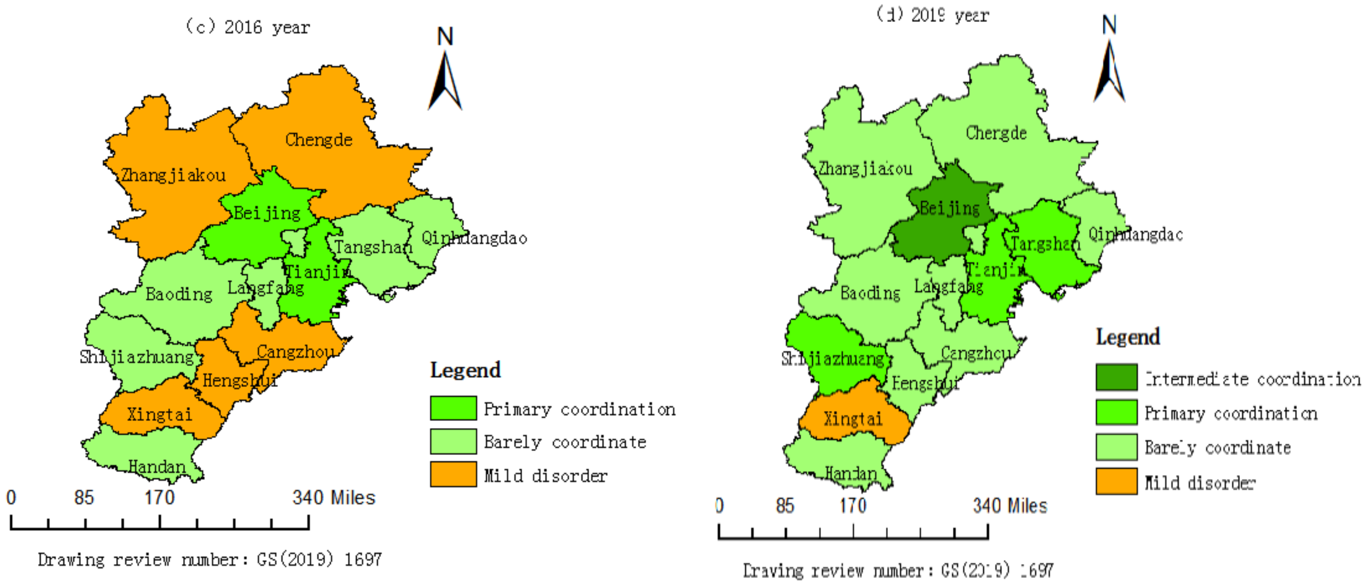

Figure 8. Spatial and temporal transition distribution pattern of coupling coordination degree in JJJ region.

(1) Middle and senior coordination stage: no cities in the JJJ region reached this stage during 2010, 2013, and 2016. In 2019, only Beijing reached the intermediate coupling coordination stage, but it has not yet reached the advanced coupling coordination development stage. Not only does this type of area incrementally increase the level of digital economy development and urban resilience, but it also forms a binding domain with neighboring domains that promote each other, and spillover effects, such as technological diffusion and factor flows, are evident. It, therefore, promotes the continuous improvement of the degree of coupling coordination of the digital economy and resilient urban development with one another, and it becomes the growth pole of regional development.

(2) Primary coordination stage: there are no cities in 2010, only Beijing in 2013, Beijing and Tianjin in 2016, and Tianjin, Shijiazhuang, and Tangshan by 2019. On the whole, the number of cities in this stage increased by 30.77% from 2010 to 2019, and the distribution is relatively stable. In the future, cities at this stage should actively introduce experience, strengthen cross-regional cooperation, and enhance soft and hard power. Promoting the coordinated development of digital economy and urban resilience to a new height is important.

(3) Barely coordination stage: only Beijing reached this stage in 2010, and Tianjin entered it in 2013. In 2016, the main cities at this stage are Baoding, Tangshan, Shijiazhuang, Qinhuangdao, Handan, and Langfang. By 2019, the main cities at this stage are Handan, Qinhuangdao, Hengshui, Baoding, Langfang, Cangzhou, Zhangjiakou, and Chengde. On the whole, the urban growth rate of JJJ region in this stage from 2010 to 2019 is 53.85%, and the spatial change in this type of area is relatively unstable, showing a relatively scattered distribution trend. At this stage, these kinds of cities should strengthen further optimization and construction, seize opportunities, and make a good start.

(4) The stage of severe disorder and mild disorder: with the exception of Beijing, other cities in the JJJ region were at this stage in 2010. Except Beijing and Tianjin, every other cities in the JJJ region were at this stage in 2013. These results show that the polarization in the JJJ region from 2010 to 2013 is very severe, showing a tendency for unbalanced development. There are Xingtai, Zhangjiakou, Chengde, Cangzhou, and Hengshui in 2016 and only Xingtai in 2019. On the whole, the number of cities in JJJ region showed a downward trend from 2010 to 2019, by 84.62%, indicating

that the level of coordinated development in JJJ region was increasing year by year from 2010 to 2019. The state is expected to dock the industry gradient transfer in the future, using digital economics to change the regional development model, as well as realizing corner overruns as quickly as possible.

3.3. Exploratory Spatial Data Analysis

3.3.1. Global Spatial Autocorrelation Analysis

Global spatial autocorrelation analysis was performed in order to further analyze the spatial agglomeration characteristics and distribution of the coupling coordination between regional digital economy and ecological economic system. The adjacency distance is used as the spatial evaluation weight to test and analyze the spatial autocorrelation of the development index and coordination index of JJJ urban agglomeration (Figure 9).

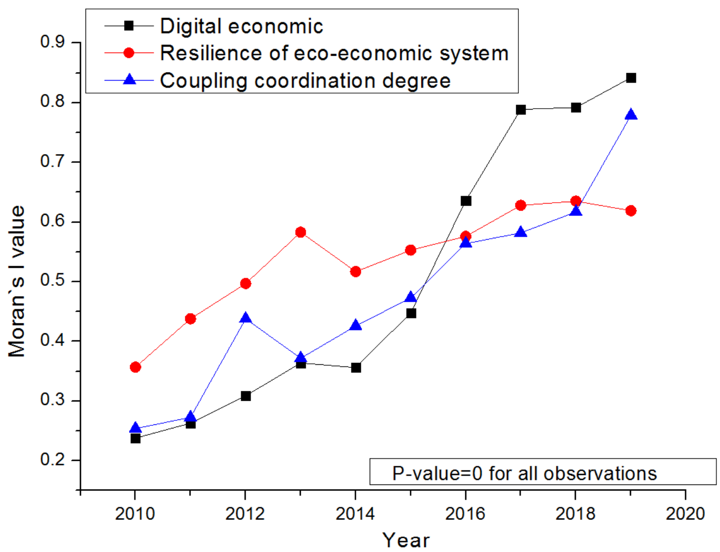

Figure 9. JJJ region digital economy and urban eco-economic system resilience (global moran's I).

It shows that the global Moran's I is greater than 0, and the Z value is greater than the critical value of confidence level (1.96). It shows that the spatial distribution of the coupling coordination degree of digital economy and urban eco-economic system resilience development index in JJJ region is not random, but it shows obvious positive spatial correlation, and the cities with high (or low) coupling coordination degree are often adjacent. From the perspective of the overall evolution trend of Moran's I, it roughly shows an upward trend of "N" fluctuation. It rose from 0.254 in 2010 to 0.438 in 2012, then it decreased to 0.426 in 2014, and then it rose to 0.779 in 2019, indicating that, with the evolution of time, the spatial autocorrelation of the coupling coordination degree of digital economy and urban eco-economic system resilience development index in JJJ region gradually increases in fluctuations.

3.3.2. Local Spatial Autocorrelation Analysis

2013, 2015, 2017, and 2019 are chosen as temporal dimensions by the natural breakpoint method. According to Formula (8), the spatial agglomeration types of digital economy and urban resilience of 13 cities in JJJ region are divided into four agglomeration types: (HH), (LH), (LL), and (HL) agglomeration area. Use ArcGIS and GeoDa software (GeoDa-1.14.0.0) to derive the LISA agglomeration map (Figure 10) to show the state of agglomeration and the spatio-temporal distribution pattern of thirteen cities.

(HH): As can be seen in Figure 10, only Beijing is located in this region as of 2013. Beijing, Tianjin, Langfang, Baoding, Shijiazhuang, and Tangshan are located in this region in 2019. Overall, this type of area gradually expanded, and the increase evidently reached 38.46%, and the distribution of spatial agglomeration tends to be more concentrated. Not only does this type of area incrementally increase the level of digital economy development and urban resilience, but it also forms a binding domain with neighboring domains that promote each other, and spillover effects, such as technological diffusion and factor flows, are evident.

(LH): In 2013, there were mainly four areas in Chengde, Zhangjiakou, Baoding, and Cangzhou in the district, and, by 2019, there were mainly two areas in Chengde and Zhangjiakou in the district. Overall, cities within the district declined by 15.38% between 2010 and 2019, with a relatively stable distribution range, and there was a low level of coordinated development in this region.

(HL): In 2013, Tianjin, Langfang, Tangshan, Shijiazhuang, and Qinhuangdao were the main districts in the region. In 2019, Cangzhou, Qinhuangdao, and Hengshui were the main districts in the region. Overall, the extent of this type of zone in JJJ decreased by 15.38% between 2010 and 2019, and area type was relatively unstable with respect to spatial change, showing a relatively dispersed distribution pattern.

(LL): There are three main areas in this area: Xingtai, Hengshui, and Handan in 2013. In 2019, there were Handan and Xingtai. Overall, the extent of the agglomeration zone shows a decreasing trend from 2010 to 2019. These results show that the level of coordinated development of the digital economy and urban eco-economic system in the JJJ region and the radiation effect of Beijing and Tianjin as the core is getting progressively better.

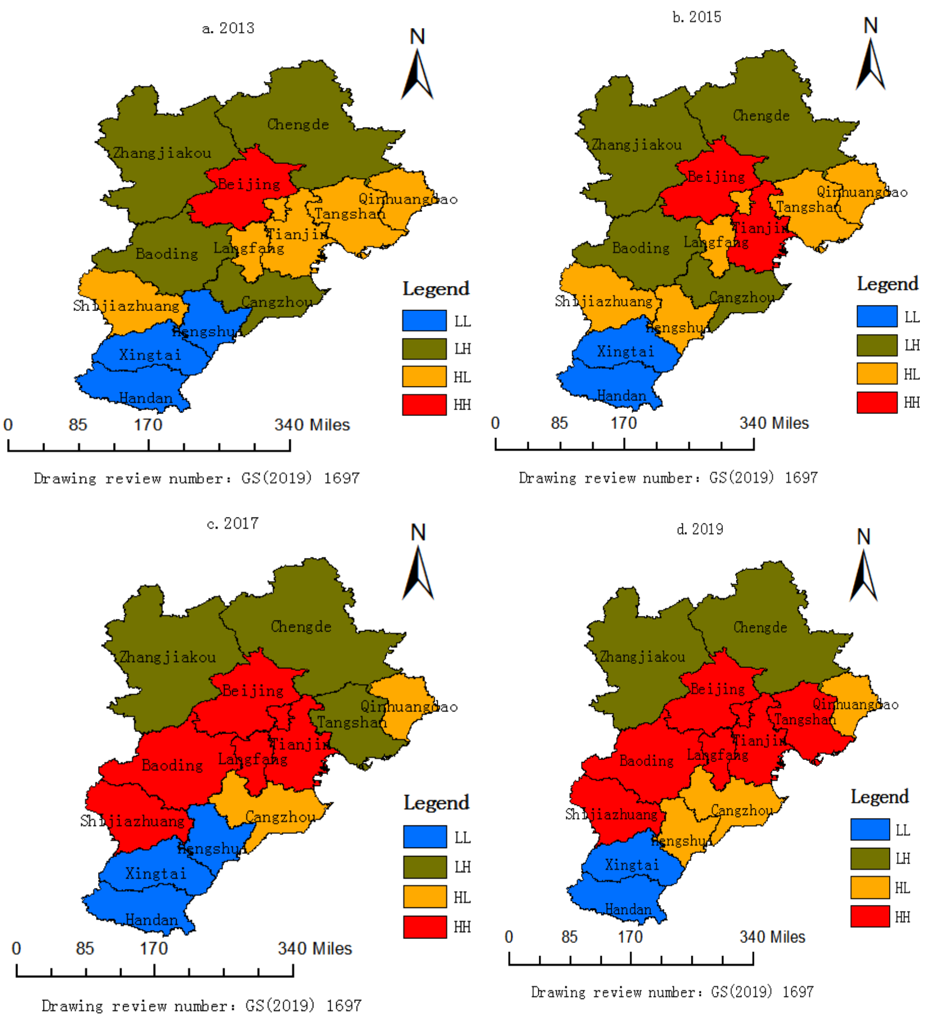

Figure 10. LISA agglomeration Map in JJJ region.

3.4. Driving Factors Analysis

Based on tests that there is some geo-spatial dependence in the coordinated development of urban agglomerations in JJJ, since it is hard for the traditional econometric model to include spatial characteristics in it [3,6], we choose the spatial econometric model.

1. Choice of influential factors

This paper combines the existing research results, as well as the current situation of uneven economic development, uneven degree of openness, uneven human capital, and urgent need to improve the development environment in JJJ region. This study summarizes seven major influencing factors. Of these, the level of economic development is the foundation [2,3,6], the operational environment of science and technology is the driving force [11,16,60], and the direction of the governmental system is the guarantee [69,78,85]. See Table 4.

2. Analysis of influencing factors

Table 4. Definition and explanation of variables related to the factors.

Influence Level	Influencing Factors	Variable Abbreviation	Measurement Index	Unit
Economic development level	Per capita income level	*PGDP*	Per capita GDP	Person/yuan
	Industrial structure	*INS*	Output value of tertiary industry/GDP	%
Operation environment of science and technology	Financial development level	*FINA*	Balance of deposits and loans of financial institutions	yuan
	The level of opening up	*FDI*	Foreign direct investment/GDP	%
	Urban informatization level	*INTERNET*	Proportion of Internet users per 10,000 people	%
Government system orientation	Intensity of environmental regulation	*ER*	Industrial pollution Control Expenditure/GDP	%
	Higher education level	*STU*	Number of college students	person

In accordance with the (9)–(11) model and with the help of Stata14.0, this paper performs a spatial econometric regression analysis on the driving factors for the degree of coupling coordination of the digital economy and the development of urban resilience in the JJJ region. Given the spatial heterogeneity of various cities in China, the dual temporal and spatial fixed-effect model is chosen. When combined with Ansilin's judgment criterion, through the comparison of the results of the adjusted R^2 and maximum likelihood estimation, we take the model (SDM) as the reference model. The landmark model uses the spatial adjacency weight matrix and, therefore, does not account for the spatial correlation of geographic distance and economic activity. For this reason, the inverse distance matrix (D) and the economic distance matrix (G) are constructed again to test the robustness of the benchmark model. The regression results (Table 5) show that the estimation results for the SDM and SEM models have not changed significantly. Only the spatial lag term in the model (SAR) becomes insignificant, but the coefficient symbols for the regressors have not changed, indicating that the results of estimating the benchmark model are robust.

Table 5. Statistics of spatial econometric regression results.

Variable	Adjacency Distance Matrix (W)				Inverse Distance Matrix (D)			Economic Distance Matrix (G)		
	OLS	**SEM**	**SAR**	**SDM**	**SEM**	**SAR**	**SDM**	**SEM**	**SAR**	**SDM**
In*FINA*	0.632	0.843	0.785	−0.937	0.823	0.786	−0.903	0.882	0.827	−0.964
In*INS*	0.836 *	0.648 *	0.776 *	0.783 **	0.623	0.738 *	0.743 **	0.628 *	0.639 *	0.728 **
In*ER*	0.238 *	0.365 **	0.327 *	0.372 *	0.683 *	0.359 *	0.382 *	0.326 **	0.349 *	0.344 *
In*INTERNET*	0.318 *	0.216 *	−0.308 *	0.116 ***	0.187 *	0.243 *	0.314 **	0.286 *	0.227 *	0.244 **
In*PGDP*	0.538 ***	0.427 *	0.386 *	0.392 ***	0.378 *	0.428 *	0.468 ***	0.382 *	0.425 *	0.378 ***
In*FDI*	0.427 *	0.458 *	−0.538	0.234 **	0.428 *	−0.536	0.252 **	0.453 *	−0.546	0.273 **
In*STU*	1.183 ***	−0.615	0.839 **	1.216 ***	−0.559	0.838 **	1.146 ***	−0.636	0.841 **	1.348 ***
In*FINA*.W				1.263	0.638	0.728	0.546	0.743	0.852	0.647
In*INS*.W				0.032 *			0.738 *			0.730 *
In*ER*.W				−1.483			−0.064			−0.056
In*INTERNET*.W				0.314 ***			0.357 *			0.443 **
In*PGDP*.W				0.649 **			0.682 **			0.739 **
In*FDI*.W				−0.683			−1.038 *			−1.458
In*STU*.W				0.792 **			0.687 *			0.656 **
P			0.245 *	0.149 **		0.649	0.118 **		0.637	0.235 **
R^2-ad	0.328	0.417	0.337	0.634	0.479	0.383	0.752	0.546	0.432	0.839
Log-likelihood		228.42	213.97	231.74	227.58	216.64	229.34	213.74	208.31	229.17
Time effect	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
Individual effect	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
Number of samples	500	500	500	500	500	500	500	500	500	500

Note: *, ** and *** are significant at 10%, 5% and 1% confidence levels, respectively.

According to the statistical results (Table 5), there are differences in the regression coefficient and spatial lag coefficient of the seven influential factors under three different spatial weight matrices. Among them, the PGDP, INS, INTERNET, and STU regression coefficients, as well as the spatial lag coefficients, are all positive and have passed the test of significance. They show that they have a positive effect on the coupling and coordinated development of the digital economy and the urban eco-economic system in this city and neighboring cities, and there is a clear positive spatial spillover effect. Note that the regression coefficients for FDI and ER are significant, while the spatial lag coefficients are insignificant, indicating that they have a positive effect on the city, but they will restrict the improvement in the degree of coupling coordination of the two neighboring cities. Neither the FINA regression coefficient, nor the spatial lag coefficient, passed significance testing, indicating that the level of financial development was not conducive to the level of coordinated development of the digital economy and the resilience of urban eco-economic systems in this city and its surrounding areas.

4. Discussion

4.1. Theoretical Value

The characteristics of the spatio-temporal evolution and the driving forces for the coupled and coordinated development of the digital economy and urban eco-economic system found in this paper are of referential importance to other countries and regions [93–96]. The findings of this paper have some reference value for the digital economy and for green development initiatives in many countries and regions. Analysis of the characteristics of spatiotemporal evolution suggests that there is a need to balance resilient coupling and coordinated development of the digital economy and urban eco-systems, as well as to fairly distribute the development resources of digital economy, so that backward areas can also benefit from the high-quality economic growth brought about by the digital economy. This significant spatial spillover effect demonstrates that, in order for development and growth to occur, it is important that cities in underdeveloped areas learn from the experience of resilient development and management of the digital economy and eco-economic system in neighboring cities.

Ultimately, depending on the path of influence, the government should improve the infrastructure construction of the urban eco-economic system and the development of the digital economy, and it should consolidate the rationalization and upgrading basis of industrial structure, consider the digital economy as the key starting point for upgrading industrial structure, and support companies in improving the innovation level of digital technology. We will constantly accelerate the exploration of new scenes and new models for the coordinated development of the urban digital economy and eco-economic system. The results of this study provide a new perspective for related research in the area of urban digital economy and eco-system resilience development under the "dual carbon" objective in China.

4.2. Practical Value

In practice, this paper comprehensively uses GIS spatial analysis technology, ESDA, nuclear density test, spatial metrology and other tools to reveal the spatio-temporal evolution pattern and driving mechanism of the coupled and coordinated development of JJJ urban agglomeration system. The purpose of this paper is to describe the spatio-temporal difference and spatial effect of the coupling and coordinated development of JJJ urban agglomeration system. An attempt is made to make differentiated policy recommendations with a view to exploring a widely replicable and accessible approach to promote the sustainable development of cities throughout the country and even in other developing countries.

According to the matrix of Boston Consulting Group (BCG), using the idea of this model for reference [97], it corresponds to the four spatial agglomeration types of JJJ urban agglomeration: "H-H, L-H, L-L, L-H". JJJ urban agglomeration should look for different ways to enhance the potential of urban development, according to its own resource endowment, development orientation, and radiation-driven ability. We will promote organic convergence and coordinated development of the innovation chain, industrial chain, and value chain in the region. H-H: this type of area should continue to maintain a good momentum of development and give full play to the advantages of digital economy, technology, and regional policies, such as the internet, big data, and artificial intelligence. Increase investment in research and development, improve the level of urban informatization, and better promote the construction and development of urban eco-economic system resilience. At the same time, we should give full play to the leading role of radiation and agglomeration economic effects of central cities and eliminate institutional barriers, such as administrative segmentation and market segmentation. Promote knowledge and technology spillover among urban agglomerations, orderly flow of factors of production and innovation resources, and improve the efficiency of resource allocation in urban agglomerations. L-L: the state should further increase support for this type of cities, dock industrial gradient transfer, narrow the digital divide gap, use digital economy and technology to change the regional development model, and realize corner overtaking as soon as possible. H-L: the coupling and coordination level of digital economy and urban eco-economic system in this type of area has development advantages compared with the surrounding areas, and cross-regional cooperation and exchanges should be actively carried out with the surrounding areas. Promote the overall improvement of the coupling and coordinated development level of the surrounding urban system in a larger space through factor spillover and development demonstration. L-H: the level of coordinated development of digital economy and urban eco-economic system in this kind of region is low, and due to the flow of capital, talent, and other factors to urban areas with a high level of development, these factors result in serious polarization problems. It is necessary for the government to properly restrain the resource siphon of the core cities to the surrounding cities by means of spatial planning and industrial guidance, strengthen the overall regional coordination, and avoid excessive gaps within the urban agglomeration. In the future, this type of city should actively undertake the spillover of innovative resources in core cities, strengthen the concept of green development, and avoid becoming a haven for pollution.

Attach great importance to the spatial correlation and non-equilibrium characteristics of the coordinated development of system coupling and give full play to the spatial spillover effect. Build a cross-regional platform for digital technology cooperation and establish a mechanism for sharing resources and technology. We will optimize the spatial structure and spatial governance of urban agglomerations in all directions, and we will form a unified, open, coordinated, and orderly spatial pattern of regional integration. Spatial structure and spatial pattern are not only the important determinants of urban agglomeration development toughness and quality, but they are also the key to effectively alleviate the contradiction between resource and environmental constraints and economic development efficiency of urban agglomeration. We will strengthen the comprehensive management of the ecological environment of urban agglomeration and the intensive utilization of resource elements. Improve the resource and environmental carrying capacity and comprehensive carrying capacity of urban agglomeration and enhance the development toughness and sustainable development ability of urban agglomeration.

4.3. Recommendations for Policymakers

Drawing on research on digital economy and the urban eco-economic system in the JJJ region, we find that the development of the digital economy and the urban eco-economic system promotes each other, co-creates value, and realizes each other. Based on the empirical analysis, we offer the following suggestions, which may have some inspiration for policy-makers.

(1) At the national level, regional digital economy planning and resilience of urban eco-system coupling collaborative development strategy should be followed, as well as following difference law, in order to achieve collaborative symbiotic development models. This is because of spatial differences and heterogeneity in resource endowments in different cities and because the effects of exogenous factors on different cities are different. As a result, the central government should adopt targeted and differentiated policies and actions depending on local conditions in order to achieve the transformation of urban planning and governance from a unified "multi-city one policy" to a flexible "one city, one policy". From a governmental perspective, we should create an environment conducive to fair competition and institutional safeguards to guide banks in improving the funding system for the development of relevant topics, and we should form a long-term sharing mechanism for efficient allocation of financial resources.

(2) The industrial structure should be actively adjusted and the positive effects of industrial structure upgrading, and rationalization on the development of both should be given full play. Additionally, we should gradually realize the high quality digital development of "economic ecology" and "ecological economization". The resilience early warning system of the urban economic-social-ecological environment system is built on the attributes of the digital economy that are driven by the scene, data, and platform. We should incorporate the benefits of the city's dynamic and visual big data development platform in diagnosing the vulnerability of the urban eco-system. These changes should be based on quantitative data, such as vulnerability and disaster carrying capacity. These processes implement the dynamic feedback mechanism of the "data governance" system and the dynamic adjustment mechanism, and they improve the resilience level of the urban eco-economic system.

(3) Given the important role that digital economy development plays in fostering the resilience of regional eco-systems, in particular, there is a need for increased investment in the development of digital economies, including the promotion of 5G, the internet of things, cloud computing, big data, artificial intelligence, blockchain, and other new generation of information and communication technologies in order to speed up innovative breakthroughs and promote the deep integration of the digital economy and the real economy. Making digital economics an important foundation for enhancing economic resilience is important.

(4) On the basis of regional differences and the existence of spatial spillover effects from the coordinated development of the digital economy and the resilience coupling of the eco-economic system, these changes should be made. In order to reduce the digital divide between regions, the government should implement a support policy that is appropriately biased towards backward and peripheral cities. Not only does it help to enhance the positive effect of the digital economic development of backward cities

on the resiliency of eco-economic systems, it also helps to foster the resilience of the eco-economic system of the central cities.

5. Conclusions

Based on the coupling effect, this paper provides a thorough analysis of the characteristics of spatiotemporal evolution, the mechanism of interaction, spatial spillover effects, and driving factors from the perspectives of economics, society, ecology, and so on. Through an empirical analysis we make the following important discoveries:

(1) From 2010 to 2019, the overall level of digital economy and urban eco-economic system resilience evaluation index in JJJ region showed a wavy upward trend, which showed a significant positive correlation. Additionally, the digital economic development index as a whole is better than the urban eco-economic system resilience development index. However, the development of the two should be a coordinated development process. Digital economy is a new driving force and new engine for the resilient construction and development of urban eco-economic system. This means that digital economy plays a more and more important role in promoting the resilient construction of urban eco-economic system.

(2) The coupled coordination model is used to quantitatively analyze the coupling coordination degree between digital economic index and urban eco-economic system resilience index. The results show that the role of mutual promotion and coordination between them has been continuously strengthened in 2010–2019. The degree of internal coordination between the two systems has gradually increased, and the degree of coupling coordination has increased steadily, especially after 2015. By 2019, the JJJ region has been in the primary coupling coordination stage. This shows that the benign coupling and coordinated development situation of the mutual promotion of digital economy and urban eco-economic system in JJJ region has been initially formed, but it has not yet reached the ideal stage of middle-and high-level coupling and coordination.

(3) Spatial analysis: JJJ region shows a positive correlation in space, and it shows certain characteristics of spatial agglomeration and distribution. The results of nuclear density estimation and analysis show that, from 2010 to 2019, with the passage of time, the nuclear density curve continues to shift to the right, the peak value continues to decrease, showing a trend from "peak" to "flat", and the shape of the curve becomes gentle. It shows that the development gap between cities in JJJ region is gradually expanding, and the convergence between cities is decreasing. The results of spatial econometric regression of the driving factors of the two coupling and coordinated development show that there are obvious spatial spillover and diffusion effects. Different influencing factors have significant differences in the coupling and coordinated development of this region and adjacent areas.

There is a complex interaction mechanism between regional digital economy and eco-economic system resilience. Vigorously developing the digital economy, releasing the dividend of industrial structure transformation, and building a new engine of economic development are important issues for China's economy to achieve green transformation and sustainable development. Digital economy will gradually become a new driving force for future economic growth, and promoting the deep integration and coordinated development between digital economy and ecological environment will be the main theme of future development. Our findings provide strong theoretical support and policy inspiration for policy makers. In the future, it is believed that the government and the market will explore a widely replicated and available scheme so as to better provide reference for the sustainable development of cities in the whole country and other developing countries.

However, this paper has some limitations and further research directions to consider. Firstly, because of the limitations and offset of the JJJ urban agglomeration analysis data, overall, it is difficult to reveal in a comprehensive and systematic way the overarching laws and characteristics of coupling and coordinated development of the digital economy and urban eco-economic system resilience in JJJ region. Further data refinement is needed to fully understand this phenomenon. In addition, it will be necessary to explore the dynamic mechanism of spatial differentiation and optimize the path of the regional digital economy and the resilience coupling of urban eco-economic system. The study of dynamic simulation and decision early warning mechanism to realize the resilience development of urban eco-economic system will be a new direction to be explored in the future.

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The Resilience of a Resettled Flood-Prone Community: An Application of the RABIT Framework in Pasig City, Metro Manila

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Abstract: Resilience measurement is an emerging topic in the field of disaster risk reduction. However, its application in Global South cities has proven to be a challenge due to the uniqueness of southern urbanisms and data challenges. As a result, the Resilience Benchmarking Assessment and Impact Toolkit (RABIT) framework has recently been developed to support resilience assessment in informal, marginalized, and disaster-prone contexts of southern cities. This paper asserts the relevance of the RABIT framework and uses it to assess the resilience of Manggahan residences, a resettled marginalized community in Pasig City, Metro Manila. Drawing on a quantitative approach and using exploratory factor analysis (EFA), the study revealed that scale, robustness, and learning attributes of the RABIT framework are strong contributors to the community's resilience. Self-organization, diversity, and redundancy have similar levels of contribution. Equality and rapidity were found to have the weakest relative contribution. The study findings emphasize the need to view resilience in resettled communities holistically and adopt an integrated and comprehensive approach that considers the multiple aspects of everyday life to proactively build adaptive and future resilient capacities.

Keywords: disaster resilience; RABIT framework; Manggahan Residences; Metro Manila; resettlement

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1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) [1], cities in the developing world are at the forefront of major hazards. These cities continue to remain major hotspots of disaster risks and vulnerabilities [2,3]. Climate change impacts, in combination with rapid urbanization and infrastructural lags, have increased the exposure of developing cities to numerous risks, such as floods [4]. Indeed, reports from EM-DAT point to an increasing trend in the frequency and intensity of flood risks [5], causing severe economic, social, and psychological stress to local people and disproportionally impacting the poor and the most vulnerable in many cities in developing countries. This situation is well-recognized and has led to an emerging consensus across the global and national levels to build the resilience of communities vulnerable to disaster risks [6,7]. Several global frameworks are in collective unison on the call to strengthen resilience at all levels. One of the foremost global frameworks for disaster risk reduction, the Sendai Framework, articulates the need to protect and strengthen the resilience of people, communities, and countries by planning for and reducing disaster risk [8]. Similarly, the Sustainable Development Goals (SDGs) explicitly call for resilience-building on multiple scales. Specifically, SDG 11 commits to ensuring cities are safe, inclusive, sustainable, and resilient. The New Urban Agenda also calls for strengthening the resilience of cities, with a particular focus on risk-prone areas such as informal settlements [9].

A key step towards strengthening resilience is by measuring it. Measuring resilience at different spatial scales to understand contextual situations, develop interventional strategies to mitigate disaster impacts, and strengthen communities' ability to recover from and successfully adapt to adverse events is a key aspect of the resilience agenda. Over the years, the concept of resilience has extensively evolved across many disciplines, including disaster management [10,11]. The etymological and conceptual changes in the concept have resulted in a proliferation of disaster resilience assessment tools and indexes with different indicators [12]. For instance, the place-based composite resilience indices illustrate the important facets of resilience [13]. In addition, the baseline resilience indicators for community resilience (BRIC), the community disaster-resilience index (CDRI), Foster's resilience-capacity index (RCI), and the disaster resilience of place (DROP) are employed to measure resilience at the provincial level [14–17]. All these resilience assessment tools have a similar objective of equipping communities to proactively adapt to, cope with, and thrive in the face of disaster events [18,19]. However, each assessment tool has its limitations.

According to Dianat et al. [20], most resilience assessment tools do not measure all attributes of resilience. Marzi et al. [21] indicated that using a composite-index approach provides a clear picture only at the higher administrative levels and neglects the inherent variability of performance at the lower levels. Most importantly, the BRIC was developed considering context-specific issues in the United States, which makes generalization and application to Global South cities difficult [22,23]. Global South cities are characterized by informal settlements, defined as areas with locational characteristics that include flood-prone areas, poor infrastructure, and low socio-economic profiles [24,25]. Even though informal settlements are a major hotspot for disaster, few resilience assessment tools apply to this context. One resilience assessment tool that considers informal settlement characteristics is the Resilience Assessment Benchmarking and Impact Toolkit (RABIT) framework. The RABIT framework was developed based on an informal context of disaster vulnerability and works within the data and skill set limitations in informal areas [26]. This study, therefore, employs the RABIT framework in a low-income resettled housing community to ascertain its resilience. Specifically, it seeks to understand from a localized informal context and with reference to the dimensions of the RABIT framework which areas are contributing better to the community's resilience and where improvements are needed to enhance resilient capacities and futures.

This research makes three major contributions. Although the RABIT framework has been used in informal contexts in Africa and Latin America, this is the first study to employ it within Southeast Asia—specifically, Manila. This helps to ascertain its relevance in disaster-hotspot regions such as Southeast Asia [27] and its role in supporting community-level resilience. Second, resilience measures often do not consider resettled areas, as if to implicitly assume the automatic transition of post-resettlement areas to resilient communities. Third, applying the RABIT framework allows a localized lens into so-called disaster-risk-improved communities to contextually understand areas that need further improvement. This allows a localized and situated perspective of previously flood-vulnerable but resettled communities as "evolutionary sites," where resilience is not static or fixed in time but rather a dynamic process of continuous adjustment [28] that needs to be constantly supported and strengthened to ensure holistic and adaptive responses to present and future risks. Fundamentally, the study contributes to ongoing policy and scholarly discussions about the relationship between housing resettlement as a disaster risk reduction strategy and community resilience.

The present study was undertaken in Manggahan Residences (colloquially referred to as Manggahan LRB) in Pasig City, one of the most flood-prone cities in Metro Manila [29]. The work proceeds as follows. Following the introduction, a literature review on resilience and resilience measurement methodologies is discussed in Section 2. Section 3 provides the context and description of the study area. Section 4 details the methodology and analysis employed in the study. Section 5 presents the results of the analysis. The last section of the paper focuses on the discussion, implications, and conclusion.

2. Resilience and the RABIT Framework: An Overview

2.1. Overview of Resilience

In recent years, the concept of resilience has been gaining currency and attention across multiple academic fields [30]. This is because it provides a workable framework for examining the way in which systems adapt, transform, and persist despite facing serious disturbance [31]. However, there continues to be debate among scholars on its definition, policy applicability, and practice [32,33]. The widely accepted definition put forth by the IPCC [34] (p. 5) defines it as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner." Keating et al. [35] (p. 26) define it as "the ability of a system, community, or society to pursue its social, ecological, and economic development and growth objectives while managing its disaster risk over time, in a mutually reinforcing way."

Recent conceptualizations of resilience proffer a non-equilibrium or evolutionary model [32,36–38]. Clark-Ginsberg et al. [39] succinctly encapsulate the evolutionary perspective of resilience as the system's capacity to be able to weather external shocks while still maintaining normal functions and eventually moving into a state of adaptation and transformation. They summarize it as resilience meaning "bouncing forward" instead of "bouncing back" [39].

For the purposes and scope of this study, we examined resilience at the community level. There are two strands of academic literature on community resilience: first, as described by Holling [40] in the socio-ecological context, and second, in the psychosocial context, as explored by Alexander [41]. Community resilience is defined as a concept that enables the community to plan, prepare for, and more successfully adapt to actual or potentially detrimental scenarios efficiently and effectively [42] (p. 148). Magis [43] describes it as the community's ability to engage, develop, and generate community resources to cope and persist in situations where there is a high degree of uncertainty and unpredictability.

2.2. Measuring Resilience

Resilience measurement has been progressively considered an essential step towards reducing disaster risk and facilitating adaptation to disasters [44,45]. The Sendai Framework has advocated for the application of scientific knowledge and evidence-based approaches in disaster risk reduction [8]. As such, methods to measure and monitor resilience have become abundant in recent years [2,42,46]. Jones [47] summarizes the scientific and evidence-based approaches to resilience measuring into objective and subjective. The objective approach to resilience measuring relies on self-assessed judgements and observations outside of those being measured [48,49]. In contrast, subjective resilience measurement frameworks involve the self-assessment of the cognitive and affective capabilities of individuals or households in responding to risk [50,51]. The objective resilience approach has numerous advantages over the subjective. For instance, the objective resilience approach adopts a fixed and transparent definition of the concept of resilience [49], allows for the comparison of different areas or groups [52], and relies on indicators that government agencies routinely collect [53].

Cutter's [15] DROP framework utilizes a system of quantifiable indicators in six dimensions: community competence, ecological, economic, social, infrastructure, and institutional dimensions. This type of assessment has focused on the county scale, as it was developed in United States [23]. Similarly, the Baseline Resilience Indicators for Communities (BRIC), which is adapted from the DROP model, is among the most consistently cited frameworks for the measurement of resilience [54]. It includes 49 indicators of community resilience [13]. Despite it being one of the few to examine resilience metrics at the community level [55], implementation in Global South contexts would be a significant challenge, as it relies on secondary data [46], where data access and availability is a major setback.

Most of these resilience measurement methodologies are reliant on existing secondary data, such as census data and statistics [56]. Unfortunately, the adoption of these resilience frameworks presents challenges to developing countries due to the paucity of such data [57,58]. Furthermore, factors that determine resilience in measurement methodologies vary between and among geographical scales, and as such, translation, for example, from the national to community level tends to be cumbersome [54,57]. Extant studies conducted at the national and regional levels seem to be inadequate for resilience analysis at the local level [23]. Moreover, Keating et al. [59] note that few community disaster resilience measurement frameworks have been implemented in the field, with none empirically validated. Departing from this, we turn to the RABIT framework.

2.3. RABIT Framework

The RABIT framework was conceptualized and developed by researchers from the University of Manchester to tackle the issues of knowledge gaps from current resilience-measurement tools. It was designed to address the lack of robust tools for measuring the baseline metrics of resilience and the evaluation of the impact of development interventions on the level of resilience [60]. The framework was designed specifically with the context of developing countries in mind. It also offers a holistic and in-depth understanding of resilience at the community level [61].

Ospina and Heeks [60] identified eight attributes as properties that communities have to a lesser or greater degree (see Table 1). These include robustness, self-organization, and learning, considered core characteristics of resilient systems and referred to as foundational attributes. The other five characteristics are redundancy, rapidity, scale, diversity and flexibility, and equality, which are enabling attributes and facilitate the operationalization of the foundational attributes [60]. The framework has already been piloted in two separate case studies involving marginalized communities in Africa and Latin America [26,61]. The two pilot studies utilized a small sample size in their assessment but nevertheless yielded emergent findings that were not brought to light in previous resilience evaluations in marginalized urban communities [26]. Surprisingly, the framework has yet to be used in Southeast Asia—a region that, according to the latest World Risk Report [62], hosts some of the cities that face the highest disaster risks. In this regard, this study hopes to contribute and extend its application in the Southeast Asia region, specifically the Philippines. More importantly, it seeks to contribute to a better understanding of community resilience and generate insights for disaster risk reduction for resilience planners and practitioners.

Table 1. The RABIT Resilience Framework (adapted from [26]).

Resilience Attribute	Definition	Indicators
Robustness	The ability of a community to sustain a level of stability amid environmental shocks and disruptions	• Physical infrastructure • Coordination between the community and local authorities in the area
Self-organization	The ability of a community to adjust itself and its protocols under the threat of serious disturbances without external influence	• Level of trust between community members • Collaboration networks • Trust in community leaders
Learning	The ability of the community to leverage past experiences to strengthen current skills and innovate and plan creatively for the future	• Awareness of present risks • Access to drills and training • Knowledge-sharing between members
Redundancy	The degree to which resources and functions are diversified in the event of a major emergency or disruption	• Contingency options • Diversified income sources • External support
Rapidity	The capacity of a community to act swiftly and access resources efficiently in emergency situations	• Access to early warning systems • Swift action in response to emergency events • Immediate support from external networks during emergencies
Scale	Access to a wide range of assets and support to facilitate recovery and overcome the deleterious effects of serious disruptions	• Contact between the community and organizations or institutions that operate at a higher level • Collaborations between the community and the private and public sector • Cross-scale relationships
Diversity	Availability of a wide variety of courses of action and opportunities to the community and its ability to innovate and improvise given the circumstances	• Variety of options available to the community • Implementation of innovative methods • Perception of change as opportunity, as opposed to a threat
Equality	Degree to which the community distributes its resources and opportunities to members of the community equally	• Participation and enhanced competencies • Inclusivity and transparency

3. Study Context

3.1. Disaster Risk and Vulnerability Context of Metro Manila

According to the World Risk Report 2022, the Philippines is ranked first in terms of risk among 193 countries worldwide, with a score of 46.82 out of 100. It is a global risk hotspot, which is reflected in its high-risk values, owing to a risk profile characterized by multiple exposures and high intensities [62].

Metro Manila, an agglomeration of 17 local government units and the nation's capital, is home to more than 13 million inhabitants [63]. Megacities such as Metro Manila are characterized by high urban density and rapid population growth, which exacerbates environmental degradation and contributes to low-quality housing and poor quality of life [24,64,65]. A report by the National Economic and Development Authority (NEDA) [66] estimates that there are approximately 556,526 informal settler families (ISFs) in the city. This translates to 1 out of every 4 Metro Manila residents currently residing in informal housing [67]. Of these, 104,000 ISFs are situated in environmentally hazardous zones such as dump sites, railways, and along waterways [66]. Flooding is a perennial threat, as an average of 20 typhoons occur in the region each year, which makes these ISFs highly vulnerable to the detrimental effects of flooding [68]. Figure 1 shows the location of Metro Manila and the areas of flood susceptibility.

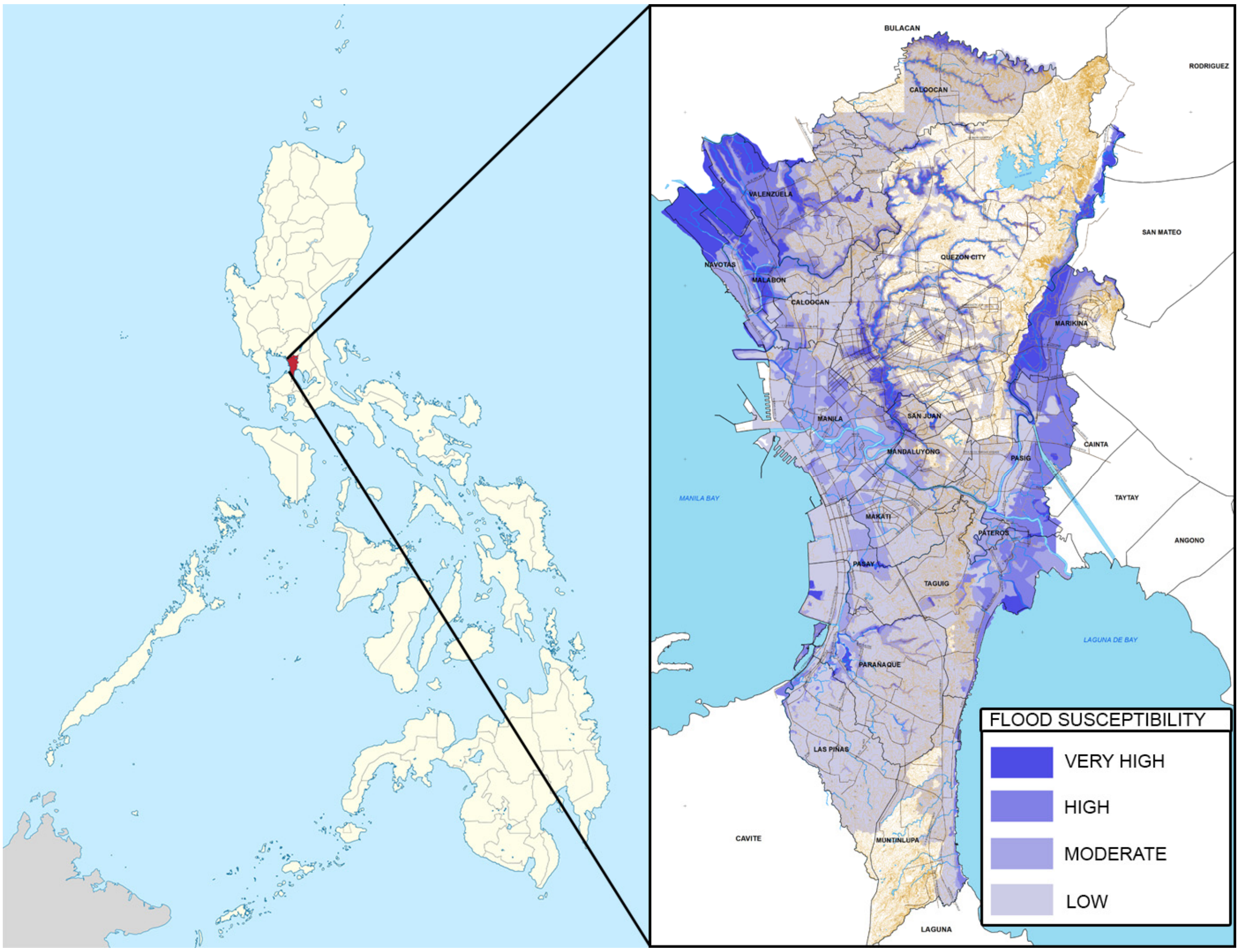

Figure 1. Metro Manila location and flood-susceptibility map (adapted from [69,70]).

3.2. Post-Disaster Resettlement and the People's Plan

On 26 September 2009, unprecedented rainfall and subsequent flooding caused by tropical storm Ketsana (known locally as "Ondoy") submerged 34% of Metro Manila. The effects were devasting for approximately 4.9 million residents, including 464 casualties, 37 missing persons, and an estimated USD 240 million in damage to property and infrastructure [71]. Following the aftermath, the national government set aside PHP 50 billion to relocate ISFs living within 3 meters of eight priority waterways across Metro Manila (Figure 2) and provide them with safer housing [72]. To gain access to the funds, affected communities were tasked to prepare and submit a community-based resettlement plan called the People's Plan [73].

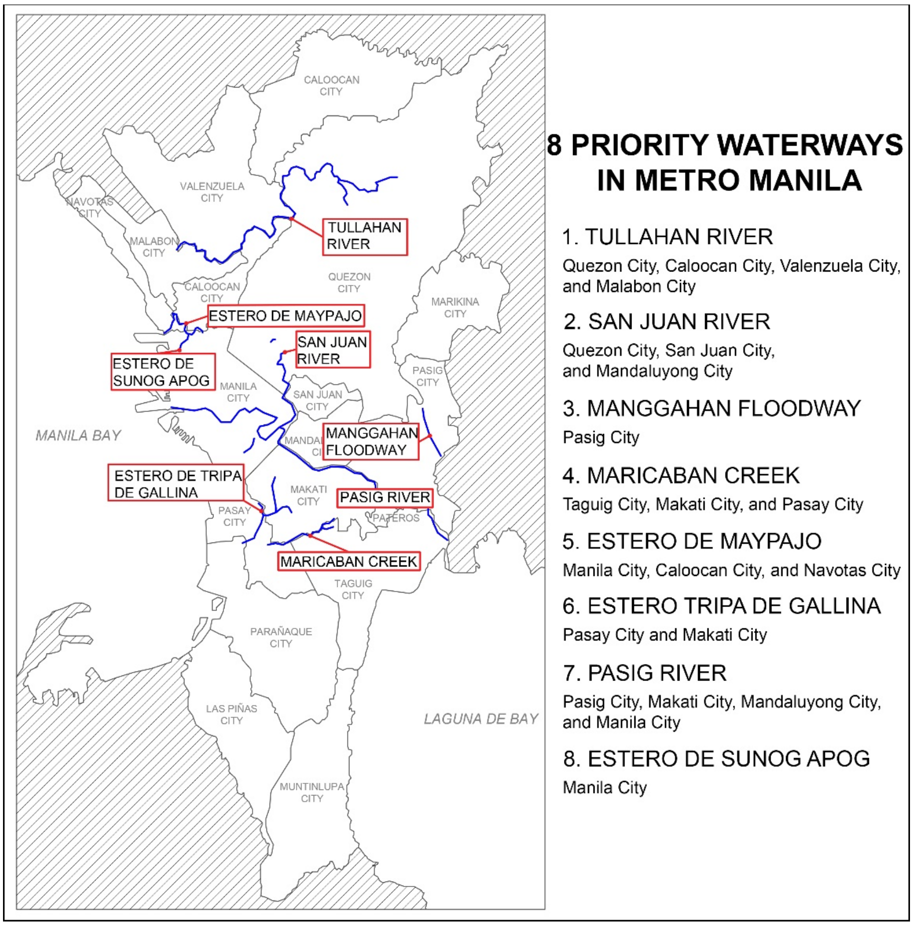

Figure 2. Waterways in Metro Manila identified as priority areas with the cities they cross (adapted from [74]).

The People's Plan is a blueprint for empowering communities and marks a shift in the conventional top-down process typically employed by the government in their resettlement programs [75]. The community is tasked to handle several responsibilities on their own, such as site selection for resettlement and negotiations with builders regarding the design and costs of the construction [73]. The process takes a considerable amount of time, with completion taking an average of six years, the bulk of which is spent on site selection, whereas only a short period of time is allocated to its design phase [76].

3.3. Study Site: The Manggahan Floodway Resettlement Project (LRB)

The Manggahan Floodway in Pasig City was constructed in 1986 to alleviate flooding in Metro Manila. Shortly thereafter, informal settlers then began occupying its embankments [75]. A Supreme Court ruling in 2008 mandated the clearing of waterways that feed into Manila Bay [72]. The catastrophic floods in the following year only served to solidify efforts to evict communities living along waterways, as the public sector looked to blame them for clogging the floodway [75,77,78].

Under the threat of eviction, 11 community organizations formed the Alliance of People's Organizations Along Manggahan Floodway (APOAMF) in 2010 with support from a local non-government organization (NGO), Community Organizers Multiversity (COM). With the help of COM, APOAMF was able to follow through with the People's Plan, navigate the complicated and lengthy bureaucratic process, and negotiate with various state actors [78]. This community-embedded process of resettlement informed the selection of the site for the case study. Specifically, the Manggahan LRB resettlement project is one of the first to employ community participation and developed along the lines of deeper engagement and dialogue with the affected residents in flood-prone areas. This provides an opportunity to empirically ascertain how so-called community-based resettlement programs shape resilient outcomes in informal settings.

Further, it needs to be mentioned that, from the government side, the project was framed around building disaster risk reduction through the resettlement [77]. It is noteworthy that in spite of the seemingly successful resettlement program, there have been some challenges, such as halted construction of the remaining buildings due to problems with the sub-contractor, the ongoing technical problems with the project's sewage treatment plant [75], and the lack of play spaces for the children in the community, which had not been planned for due to the short design phase allotted for the project [79].

At the time of this study, the project had housed some 573 households. These households were resettled from the nearby east and west embankments of the floodway, which are severely vulnerable to floods (Figure 3). The project has a total of 15 planned buildings, of which only 10 have been completed. Each building has a total of five floors, with each floor containing 12 units. A community member is elected to serve as a representative for their building. The building representative is also supported by five leaders, each in charge of one floor. It is through this community structure that functions such as information dissemination and rule enforcement are enabled [80]. The Manggahan LRB community also has an established organizational structure with committees assigned to deal with issues and concerns within the resettlement project. A Disaster Risk Reduction (DRR) committee, for example, is tasked to facilitate DRR drills and training conducted in the community. These drills and training are provided by the local government as part of their DRR capacity-building mandate [63]. Due to the COVID-19 pandemic, however, these drills have been suspended.

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

Figure 3. (**a**) Location of the resettlement project (source: Google Earth); (**b**) multi-story housing units in the resettlement project (source: author).

4. Methodology

4.1. Data and Sample Collection

To test the resilience of the study area to multiple hazards (typhoon, fire, flood, and earthquake), survey data were collected from 236 participants in the Manggahan LRB community in Pasig City, Philippines, using the simple random-sampling technique. The questionnaire was administered with a combination of face-to-face and pen-and-paper methods. The data field study was conducted from July to August 2022, spanning a period of 2 months. Before data collection, the researchers conducted a reconnaissance survey (5–11 July 2022) to become familiar with the topography of the study area and build a good rapport with members of the community and leaders. With the help of the community leaders, a reference group was formed to help create awareness about the study and encourage the residents to voluntarily take part. In addition, the community reference group evaluated the questionnaire and made recommendations for the structure and wording of the survey instruments. This helped to improve the readability of the questionnaire survey. The questionnaire was then pretested (12–15 July 2022) using 10 respondents who were conveniently sampled from the study area as a further step to improve and finetune the questions. Collection of survey data was conducted over the course of one month (20 July–18 August 2022).

The target sample size was determined using Slovin's formula based on the total households (573) in the community. Based on the total households, a confidence level of 95%, and a margin error of 5%, 231 households were determined to be the optimal sample size. Survey collection was implemented based on 10 clusters, corresponding to the existing 10 low-rise buildings currently occupied in the study area and using a simple random-sampling method to select participants/households.

The questionnaire surveys employed for the study comprised three sections. The first section was made up of the inclusion criteria, participant information sheet, and consent form. The second part of the questionnaire entailed respondents' demographic information, such as gender, age, education, employment status, marital status, and monthly income. Section 3 of the survey instrument consisted of adopted questions underpinning the variables of the RABIT Framework.

4.2. Measures

A validated survey instrument from Haley et al. [26], which conceives resilience as eight attributes, was adapted for this study. These resilience attributes include learning, robustness, rapidity, scale, diversity, flexibility, equality, and redundancy. Each attribute was measured using a Likert scale of 1–5 (1 = strongly disagree and 5 = strongly agree). This instrument provides a holistic and measurable approach to resilience and design to fit the characteristics of marginalized and informal communities—high-risk locations, high population density, and economic and political marginalization. Appendix A provides details of the instrument employed in this study.

4.3. Data Analysis

Prior to data entry, the questionnaires were screened to ensure the data for further analysis was error-free and inconsistencies were rectified. Preliminary analysis was undertaken to check for missing variables and outliers. Descriptive statistics were run for the demographic data using percentages, means, and standard deviation. This was followed by exploratory factor analysis (EFA) and construct validity and reliability tests. The EFA was used to summarize the variables and identify the factors (attributes of resilience based on the RABIT framework) and their contribution to resilience. The contribution of the factors to the overall resilience was based on the eigenvalues and percentage of variance of each factor.

5. Results

The socio-demographic characteristics of the study participants are summarized in Table 2. In this study, 79.2% of the respondents were females, whereas the remaining 20.8% were males. Concerning the age cohort of the sampled population, the majority, comprising 35.6%, were aged 45–54. The results also show that 52.5% of respondents were married, whereas 52.1% had secondary high school education and more than one-third were employed.

Table 2. Characteristics of respondents.

Demographic Factors	Components	Percentage (%)
Gender	Female	79.2
	Male	20.8
Age	15–24	6.8
	25–34	13.1
	35–44	22.5
	45–54	35.6
	55–64	18.2
	65^+	3.8
Marital status	Single	13.6
	Married	74.1
	Separated	4.2
	Widowed	8.1
Employment status	Employed	39.4
	Unemployed	16.5
	Retired	3.0
	Student	4.7
	Housewife	36.4
Educational background	Primary school/junior high school	19.9
	Senior high school	52.1
	Vocational (post-SHS)	15.7
	Tertiary (undergraduate and postgraduate)	11.4
	No formal education	0.8
Level of income (PHP)	11,001–22,000	25.8
	22,001–44,000	4.2
	44,001–77,000	2.1
	Less than 11,000	62.3
	Prefer not to answer	5.5

5.1. Exploratory Factor Analysis

In most cases, researchers do not perform exploratory factor analysis (EFA), particularly when the instrument employed in the study is an adapted scale. In this study, the researchers conducted EFA to identify variables that adequately explain the construct in the Philippines context. This was based on Juliawati et al.'s [81] assertion that a scale previously validated is not necessarily valid in a different location, time, and context.

Tables 3 and 4 show the results for the exploratory factor analysis (EFA). Before coming to that, the Kaiser–Meyer–Olkin test indicated that the sample was adequate for the analysis, as evidenced by the score of 0.910, which is higher than the suggested threshold point of 0.6 [82]. The Bartlett test of sphericity was also significant (X^2 = 4856.270, df = 741, p = 0.000), indicating that the correlation between the variables was not equal and, consequently, fit for a factor analysis. Table 3 shows the proportion of variance explained by the factors. Only factors with eigenvalues above 1 were retained, which is the acceptable level used for EFA [83]. In all, eight factors were reported to have the eigenvalues above 1. Out of this, the first component had an eigenvalue of 12.918, which corresponds to 33.12% of the total proportion of variance explained.

In all, the eight factors accounted for 63% of the total variance that explained the resilience, which is above the 50% criterion that Samuels [84] and Streiner [85] recommend as the minimum threshold. Table 3 also reports on the rotation sums of squared loadings, which represent the distribution of the variance after the varimax rotation. According to Costello and Osborne [86], the varimax rotation adds another layer to EFA by clarifying the relationship among the factors. The rotation seeks to maximize the variance shared among the component by increasing the squared correlation of items and decreasing the correlation of items that are dissimilar. Here, we observed that the proportion of the variance explained by the first component was 16.66%. The remaining component showed more even variances.

Table 3. Proportion of total variance explained.

Factors	Initial Eigenvalues			Extracted Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	**% of Var**	**Cumm%**	**Total**	**% of Var**	**Cumm%**	**Total**	**% of Var**	**Cumm%**
1	12.918	33.124	33.124	12.918	33.124	33.124	6.498	16.663	16.663
2	2.456	6.298	39.423	2.456	6.298	39.423	3.086	7.913	24.575
3	2.297	5.889	45.312	2.297	5.889	45.312	2.932	7.519	32.094
4	1.812	4.645	49.957	1.812	4.645	49.957	2.650	6.795	38.889
5	1.716	4.399	54.356	1.716	4.399	54.356	2.600	6.667	45.556
6	1.327	3.402	57.758	1.327	3.402	57.758	2.468	6.328	51.884
7	1.147	2.941	60.699	1.147	2.941	60.699	2.293	5.880	57.764
8	1.099	2.818	63.517	1.099	2.818	63.517	2.244	5.753	63.517
9	0.971	2.490	66.008						
10	0.959	2.459	68.467						
11	0.896	2.296	70.763						
12	0.807	2.070	72.833						
13	0.738	1.933	74.766						
14	0.686	1.893	76.659						
15	0.646	1.759	78.419						

Table 4 reports on the factor loadings of the individual items on the eight factors reported in this study. In line with arguments made by Pantouvakis and Psomas [87], we removed coefficients of items that were below 0.6 and reported only items with a coefficient above 0.6. Table 4 shows that the reported items with coefficients above 0.6 for factor 1 corresponded to the scale attribute of resilience. Further, Table 4 shows that the reported items with coefficients above 0.6 for factor 2 corresponded to the robustness attribute of resilience. Similarly, items with coefficients above 0.6 for factor 3 corresponded to the learning attribute of resilience. However, items such as "We have access to drills and other training activities and take part in them" (learning 3) had items below 0.6 and therefore were excluded (Table 4). Items with coefficients of more than 0.6 in factor 4 corresponded to the self-organization attribute of resilience. However, the item "I am ready to assist my neighbors during emergencies and trust that they will do the same for me" (self-organization 1) was excluded because it had a coefficient below 0.6.

Further, items with coefficients above 0.6 in factor 5 corresponded with the diversity attribute of resilience; however, similar to those items in the other highlighted attributes, the item "Our community is made up of members with a diverse set of skills and training" (diversity 4) was excluded from the list of items in factor 5 because it did not meet the 0.6 threshold. In summing up Table 3, after careful analysis of the factor loadings for factors 6, 7, and 8, we concluded that these factors represent the redundancy, equality, and rapidity attributes, respectively, of resilience based on the items loaded in these factors. Therefore, the various attributes of resilience can be ranked by their contribution to resilience in the following manner: scale, robustness, learning, self-organization, diversity, redundancy, equality, and rapidity.

5.2. Reliability and Validity

In this study, we used Cronbach's alpha and composite reliability to measure the internal reliability of all the constructs. As depicted in Table 5, Cronbach's alpha for all eight constructs was between 0.83 and 0.87, which meets Hair et al.'s [88] recommendation of 0.70. Moreover, the composite reliability for the eight constructs was found to be between 0.82 and 0.87 f, aligning with the widely accepted minimum criteria of a composite reliability greater than or equal to 0.70. We also computed the constructs' convergent validity, utilizing the recommended standards by Hair et al. [88]. First, the factor loadings and significance levels of each construct were assessed. All factor loadings were higher than 0.60 and significant at 0.01. The average variance extracted (AVE) was measured, and the results demonstrated that the AVE of all the constructs exceeded the 0.50 threshold.

Table 4. Rotated-components matrix of dimensions of resilience.

Variables	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Factor 8
Scale 1	0.781							
Scale 2	0.791							
Scale 3	0.754							
Scale 4	0.819							
Robustness 4		0.718						
Robustness 5		0.704						
Robustness 6		0.752						
Robustness 7		0.681						
Robustness 8		0.658						
Learning 1			0.857					
Learning 2			0.794					
Learning 4			0.684					
Self-organization 2				0.881				
Self-organization 3				0.797				
Self-organization 4				0.689				
Diversity 1					0.872			
Diversity 2					0.759			
Diversity 3					0.747			
Redundancy 1						0.776		
Redundancy 2						0.867		
Redundancy 3						0.759		
Equality 1							0.840	
Equality 3							0.755	
Equality 4							0.790	
Rapidity 1								0.878
Rapidity 2								0.781
Rapidity 3								0.697

Table 5. Descriptive, reliability, and validity statistics.

Construct	Descriptive		Reliability		AVE
	Mean	Standard Deviation	Cronbach's Alpha	Composite	
Robustness	2.39	0.73	0.84	0.83	0.50
Self-organization	2.64	0.89	0.83	0.83	0.63
Learning	2.22	0.86	0.84	0.82	0.61
Redundancy	2.63	0.86	0.87	0.85	0.66
Rapidity	2.36	0.97	0.84	0.83	0.62
Scale	2.31	1.11	0.88	0.87	0.62
Diversity	2.42	0.89	0.85	0.84	0.63
Equality	2.54	0.93	0.84	0.84	0.63

We utilized the Fornell–Larcker criterion to assess the discriminant validity of the constructs. According to Fornell and Larcker [89], when the square root of the AVE is higher than each construct's correlation (diagonal values in bold), a discriminant validity has been achieved, as shown in Table 6.

Table 6. Correlation matrix and square root of AVE.

Factors	1	2	3	4	5	6	7	8
Robustness	**0.71**							
Self-organization	0.53	**0.79**						
Learning	0.13	0.13	**0.78**					
Redundancy	0.44	0.10	0.16	**0.81**				
Rapidity	0.11	0.31	0.19	0.21	**0.79**			
Scale	0.09	0.14	0.10	0.26	0.14	**0.79**		
Diversity	0.02	0.06	0.25	0.13	0.05	0.28	**0.79**	
Equality	0.04	0.13	0.02	0.05	0.03	0.10	0.10	**0.71**

NB: square root of AVE (diagonal) in bold.

6. Discussion

The results generated and the analytical framework provide insight into the study area's resilience. First, the reliability and validity tests show that the RABIT framework is a valid and suitable method for assessing the resilience of the Manggahan LRB community. As a result, the study supports the assertions made by Heeks and Ospina [90] that the RABIT framework is suitable for low-income and marginalized contexts. The EFA result reveals that each of the eight attributes contributed to resilience, although there were both variations and similarities among the attributes in terms of the strength of their overall contribution, which was basically assessed using the eigenvalues and percentage variance of each attribute. Indeed, the findings indicate that when ranked from the largest to smallest contributor to resilience, the attributes can be ranked as follows: scale, robustness, learning, self-organization, diversity, redundancy, equality, and rapidity. Further, the findings from the EFA also show that the scale attribute contributed largely to resilience in the study area relative to the other attributes. This finding is informative and shows that, depending on the study context, the contributions from the eight resilience attributes may not be the same. For instance, utilizing the RABIT framework, Haley et al. [26] found that in Masiphumelele, a low-income community in South Africa, the strength of resilience was based on the contribution of self-organization and scale. Understanding why some of the attributes play a more significant impact in fostering resilience in different low-income communities is an interesting issue to explore.

In our study, scale was identified as the most important contributor to resilience in the study area. Scale, according to Folke et al. [91], borders on the breadth of resources that is available and can be utilized by a community to effectively overcome the impact of a disaster or disturbances. Resources can take varied forms and may include natural, physical, financial, and social capital, as well as other support systems available to the community. In the context of the current study, it can be argued that the community's long-standing relationship and support received from COM has been beneficial to the Manggahan LRB community, as they have been able to foster multiple partnerships and leverage these support systems to overcome threats of eviction and call for support from the local and national governments. One of the results of these partnerships is the People's Plan, which provides an opportunity for broader engagement to promote resilience. Thus, strong partnership with NGOs is instrumental to the resilience building of the Manggahan LRB community, and it is therefore not surprising that a stronger coefficient was reported for items such as such as scale 2 ("The community has strong collaborations with the local and national government") and scale 4 ("The community has regular interactions with NGOs, academic organizations, etc. on disaster preparation and response"). Similarly, several studies have pointed to the importance of community–institutional collaborations as a form of social capital (bridging networks) in building community resilience [92–96]. This highlights the need to not only invest in physical infrastructure but also to foster collaboration and strong partnerships to provide opportunities for exchanges and flows of ideas, expertise, and resources that can be leveraged in times of difficulties. These collaborations and partnerships, as a form of social infrastructure, can help resettled communities to better anticipate and overcome future disasters [97].

The next attributes that made an almost similar contribution to resilience in the Manggahan LRB community after scale were robustness and learning. Robustness essentially refers to the ability of the community to sustain itself from shocks and disruptions and ensure some level of stability [26]. Robustness undoubtedly requires essential infrastructure and collaboration with state and non-state actors. Indeed, the government implementation of the resettlement plan has been instrumental in reducing the vulnerability of the resettled community, since it provides safe housing and essential services and infrastructure required for improved living [98]. Though opposed at the initial stages, the plan came to fruition due to the successful engagement with stakeholders such as the government and NGOs. The strong coefficient for robustness items highlights the relevance of improved housing and infrastructure in resilience building. Learning as an attribute of resilience has been found to have strong links with access to DRR-related drills and training. Cui and Han [99] argue that by participating in drills, training, and other forms of capacity building, the community can improve its resilience and recover from systemic disturbances. In the study area's case, the COVID-19 pandemic led to the suspension of DRR-related drills and training in the community for the past two years. Nonetheless, the influence of past learning experiences had some level of impact on residents, given the contribution it made towards building the resilience of residents. Indeed, there were high coefficients for items such as learning 2 ("I have received and shared lessons from past experiences with flooding from other members") and learning 4 ("The community leverages past experiences to anticipate and plan differently in the future"), which clearly indicate that residents' learning experiences with past disasters have been instrumental in shaping their preparedness for future disaster occurrences.

The next attributes that made almost similar contributions to resilience were self-organization, diversity, and redundancy. Beginning with self-organization, it highlights how a community can adjust itself and its practices under serious threats or pending disturbances. The community partnership forged between other organizations such as COM and APOAMF to follow through with the People's Plan and effectively mobilize themselves and work with their leaders to negotiate and implement the resettlement program is a clear case in point. Indeed, items with a strong coefficient for self-organization indicate strong trust in leadership, participation, and mobilization. This finding corresponds to previous studies on self-organization in similar low-income, informal, and marginalized communities in Accra, where community adjustments are made possible through collaboration, network building, and trust in community structures [100,101].

In the case of diversity, it can be argued that the community made efforts to increase the range of options to press home their demands for more support and engagement. It is not surprising, therefore, that there were strong coefficients for diversity 2 ("I am able to identify potential opportunities emerging from change") and diversity 3 ("The community comes up with innovative and creative solutions to problems that arise in times of emergency"). Despite the point made for diversity, there were difficulties that the community faced that limit their ability to take action to promote its interests. For instance, its status as a resettled community means that they still must depend on the government for many of the services they need. In the case of redundancy, it can be argued that the support gained from external bodies such as livelihood programs from women-led international NGO Huairou Commission [102] could also have contributed to building the community's resilience. Nonetheless, it needs to be mentioned that although the community has been able to leverage the support they received from COM to fight against the eviction orders, they are still dependent on the government resettlement project for infrastructure and basic amenities. The challenges highlighted for diversity and redundancy explain why they did not contribute much to resilience in the community.

The two attributes that made the smallest contribution to resilience were equality and rapidity. Equality entails the fair distribution of opportunities and capacity-building programs and fostering participation among all members of the community. Promoting inclusivity and participation among members of the community has been found to be instrumental in quick and effective outcomes for improvement [103,104]. In the context of this study, delays in resettling all the disaster-prone households (only 573 have been resettled out of 900 households) and lags in providing infrastructure facilities, such as issues with the sewage-treatment plant for the entire community [78] and the lack of public spaces and playgrounds for children [79], might explain the comparatively limited contribution of equality to the resilience in the study area.

Rapidity, or swift access to assets such as disaster-related information and resources, is the factor that contributed the least to the community's resilience. Although early warning systems (EWS) are already in place to disseminate disaster-related information [71] in the community, previous studies indicate that access to disaster risk information and communication channels embedded in existing social structures and timely updates improve preparedness and adaptive capacities [100]. Moreover, this points to the importance of an information system that leverages community trust and leadership to further enhance the community's receptiveness and alertness towards disaster risk information and therefore influences their intentions to prepare for present and future risks [105,106].

7. Conclusions

This study contributes to the emerging research on resilience measurement at the community level. It applied the RABIT framework, a community-level resilience measurement tool, to assess the resilience of a resettled informal settler community displaced because of the catastrophic 2009 floods in Metro Manila. The study also demonstrates its utility and relevance in evaluating resilience at the community level, focusing on marginalized urban communities. Resilience attributes were assessed and validated regarding whether they were statistically significant factors in the community's resilience. Analysis of the survey data revealed that although all attributes are statistically relevant, their contributions towards the community's resilience vary. The results show that the attributes of scale, robustness, and learning proved to be relatively strong contributors to the community's resilience. Self-organization, diversity, and redundancy were found to have similar levels of contributions. The attributes of equality and rapidity were found to be relatively weaker and thus require more attention. The study has shown that although the Manggahan LRB community and its resettlement as a DRR approach is seemingly trending towards a resilient outcome, there remain some challenges to be revisited that merit closer scrutiny.

This research provides a case study for the practical measurability of the attributes of community resilience as prescribed in the RABIT framework. However, the study is limited in its scope of generalization and application for three reasons. First, the RABIT framework used does not account for mental or psychological attributes of resilience [107,108] in post-resettlement situations. Measuring mental outlook or psychological aspects in future studies is important to understand how resettlement communities view their future and are prepared for future uncertainties and risks, as evidenced by the stresses of the current pandemic in informal communities. Second, the current study only provides a snapshot of the community's resilience through a quantitative lens. Further research is needed to support the quantitative results with qualitative data (e.g., interviews and focus group discussions) to provide more holistic depth in the assessment of resilience attributes. Finally, focusing on a single case without a comparative or experimental analysis with another community limits the generalizability of the present study. Future experimental or comparative analysis might provide more insight and allow for generalization. Nevertheless, this study puts forth its contribution towards testing community resilience measurements in the understanding that these measurement tools do not necessarily translate to instantly shaping a particular community to be resilient but can be considered a decision-making tool for disaster risk reduction and resilience managers to prioritize and direct resources to critical areas necessary for building adaptive and resilient capacities of marginalized communities in Metro Manila and other Global South cities.

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Appendix A

1. Survey-Respondent Profile

1.1 Name: ____________________

1.2 Sex

- o **Female**
- o **Male**

1.3 Age

- o **15–24 y/o**
- o **25–34 y/o**
- o **35–44 y/o**
- o **45–54 y/o**
- o **55–64 y/o**
- o **More than 65 y/o**

1.4 Marital Status

- o **Single**
- o **Domestic** partnership
- o **Divorced**
- o **Widowed**

1.5 How many are you in the household?

- o 1
- o 2–3
- o 4–5
- o More than 5

1.6 Educational Background

- o No formal education
- o Primary/JHS
- o Secondary/SHS/vocational
- o Tertiary

1.7 Occupation

- o Unemployed
- o Student
- o Housewife
- o Self-employed
- o Private company employee
- o Government employee
- o Retired

1.8 Monthly household income

- o Less than 11,000
- o 11,001–22,000
- o 22,001–44,000
- o 44,001–77,000
- o 77,001–132,000
- o More than 132,000
- o Prefer not to answer

1.9 How long have you been living in this community?

- o Less than a year
- o 1–2 years
- o 3–4 years
- o 5–6 years
- o More than 7 years

1.10 Which type of natural hazard have you experienced? (You may select more than one.)

- o Floods
- o Earthquakes
- o Typhoons
- o Fires

2. Resilience Attributes

2.1 Robustness

I do the necessary preparations to anticipate and respond to flood disasters/emergencies.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
The building I live in is safe against hazards such as flooding.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
The building I live in is safe against typhoons.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
The building I live in is safe against earthquakes.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
The building I live in is safe against fires.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Lifeline utilities such as electricity and water are easily restored following a disruption.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Assistance from the government (e.g., rescue, fire brigade) is accessible to the community during emergency situations.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Community infrastructure is **strong to prevent or mitigate impacts from disasters such as flooding.**	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
2.2 Self-Organization					
I am ready to assist my neighbors during emergencies and trust that they will do the same for me.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Local leaders are highly capable and are able to perform their duties responsibly during emergencies.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
I regularly participate in disaster-prevention and -response programs initiated in the community.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Local groups (e.g., DRM) actively participate in disaster preparation and response.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
We adopt technology to mobilize resources for disaster preparedness and response.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
2.3 Learning					
I am knowledgeable of the severity and places of high flood risk in our area.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
I have received and shared lessons from past experiences with flooding from other members.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree

We have access to drills and other training activities and take part in them.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
The community leverages past experiences to anticipate and plan differently in the future.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
2.4 Redundancy					
We maintain an emergency fund just in case of serious disruption to our livelihood.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
I have diversified income sources to sustain me in times of emergency.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
I have access to financial instruments such as insurance or informal group credit.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
I receive support from family, friends, and neighbors in times of emergency.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
2.5 Rapidity					
I have access to early-warning and up-to-date information on upcoming flood hazards and other emergency events.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Emergency information is rapidly disseminated among members of the community.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
We are able to swiftly implement evacuation protocols should a disaster occur.	○ Strongly	○ Disagree	○ Neutral	○ Agree	○ Strongly
	Disagree				Agree
We are able to promptly receive emergency aid and/or food after a disaster has occurred.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Local leaders and institutions effectively coordinate emergency-preparation and -response activities.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
2.6 Scale					
The community has various partnerships with NGOs, academic organizations, and even international agencies.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
The community has strong collaborations with the local and national government.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
We have received aid (e.g., scholarships, skills training, health services, etc.) as a result of these types of partnerships.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
The community has regular interactions with NGOs, academic organizations, etc., on disaster preparation and response.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree

2.7 Diversity and Flexibility					
I have several options or courses of action available to me in case of emergencies.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
I am able to identify potential opportunities emerging from change.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
The community comes up with innovative and creative solutions to problems that arise in times of emergency.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Our community is made up of members with a diverse set of skills and training.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
2.8 Equality					
I feel my needs and opinions are considered in the decision-making process of our community.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
The decision-making process on disaster management in our community association is transparent.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Resources on disaster management such as aid are distributed fairly among members of the community.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
Capacity-building programs and opportunities are available to all, including marginalized groups (e.g., PWD, youth, elderly).	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree
I am involved in making decisions about steps to undertake against the effects of natural hazards such as flooding, typhoons, etc., that affect me.	○ Strongly Disagree	○ Disagree	○ Neutral	○ Agree	○ Strongly Agree

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Coupled and Coordinated Analysis of Urban Green Development and Ecological Civilization Construction in the Yangtze River Delta Region

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Abstract: Managing the human–nature relationship is key to facilitating the sustainable development of cities. The coupled coordination relationship between ecological civilization construction and urban green development and influence of spatio-temporal heterogeneity has been insufficiently studied. We used the coupled coordination degree model (CCDM) and spatio-temporal weighted model (GTWR) to analyze the relationship and heterogeneity between ecological civilization construction and UGD and ECC in each city in the Yangtze River Delta region from 2010 to 2019. The results show that: (1) UGD and ECC coordination levels fluctuated more from 2010 until 2019. There was a transition from lagging UGD and ECC to lagging ecological civilization construction and a decreasing degree of coupling coordination in the Yangtze River Delta region from east to west from near imbalance to primary coordination. (2) The Yangtze River Delta's negative UGD and ECC effect was concentrated in northwest inland cities; the positive UGD and ECC effect was concentrated in southeast coastal cities. Thus, UGD and ECC and ecological civilization construction complement each other. This study provides a scientific basis for analyzing the coordination between ecological civilization construction and UGD and ECC and provides practical guidance for formulating and implementing urban high-quality development countermeasures.

Keywords: Yangtze River Delta region; ecological civilization construction; urban green development; coupled coordination degree model; spatio-temporal weighted regression model

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1. Introduction

The 20th Party Congress report of the Chinese Communist Party outlined specific requirements for the creation of novel concepts that "enhance system for building ecological civilization, accelerate urban green growth, and promote to live in harmony of humans and nature" [1]. The Party and State attach a high level of importance to the promotion of an ecological civilization by the municipal government. This has highlighted the new strategic concepts behind the new development pattern of the double cycle of cities, and the positive contribution to socio-economic development and sustainable development. Li [2] has defined ecological civilization as a natural ecological and environmental civilization that depends on the exchange of human knowledge and wisdom, relies on a healthy ecological and natural balance, and coordinates urban, social, and economic growth with overall growth of the global economy. According to Gu [3], an ecological civilization is a high-quality culture that reflects the harmonic relationship between humans and nature, constitutes modern human civilization, and has strong contemporary relevance. Cities are the primary site for ecological civilization construction (ECC), and urban green development (UGD) should prioritize ECC, promote urban informatization, greening, and sustainable development. This should be undertaken through green urban economic growth and attach importance to the coordinated development of the urban economy, society, and culture. It should also emphasize resource-intensive industries to raise environmental awareness. In terms of layout and direction, UGD is a long-term driving force for building ecological civilization. Therefore, studying the interaction mechanism and evolution law of UGD and ECC has become a popular research topic. Many studies have investigated the relationship between UGD and ECC from various perspectives, including urbanization [4], e-commerce [5], economic development [6], energy consumption [7], and environmental pollution [8,9]. These empirical studies provide important references for further exploring the coupled and coordinated relationship between UGD and ECC. However, most prior studies in the field have primarily focused on the qualitative relationship between UGD and ECC and the study of the coordination within a single system, while disregarding the coordination relationship and inner mechanism between UGD and ECC. To date, there has been relatively little research on the coupling connection between UGD and ECC from a quantitative perspective of the composite system. This is not conducive to in-depth exploration of the interaction and degree of influence between urban–ecological civilization.

The term "ecological civilization" was first proposed by Professor Iring Fetscher [10] in Germany. However, no relevant definition was given in his work. For the exploration of the connotation of ecological civilization, foreign scholars have conducted relevant studies from multiple levels, perspectives and multidisciplinary integration, such as exploring the relationship between Marxist ideology and ecological civilization [11], building global democracy to develop ecological civilization [12], establishing an ecological economy to explore the roots of ecological civilization [13], improving the political economy framework to pursue practical steps towards ecological civilization [14], and building a global ecological civilization system by creating new paths of sustainable development to replace traditional economic development models [15]. The idea of green development began to emerge from abroad when Rachel Carson [16] argued in the *Silence of Spring* that the natural world on which we depend is being destroyed by man's uncontrolled use of chemical pesticides. This was the first time that man stood up for man and nature and revealed the negative effects of scientific progress. In 1970, an eco-justice campaign on the theme of 'ecological economic value theory and sustainable development theory' erupted in the USA, revealing a shift towards the practice of green development, as reflected in ecological economic value theory, and emphasizing how the ecological core of green development is a solution to environmental protection through sustainable development rather than simple confrontation [17]. The concept of green development has caused considerable controversy in the West. This concept has caused quite a stir in Western countries. Starting in the 1990s, the global green movement began to emerge, from 'green production' to 'green consumption' [18,19], from "from 'green logistics' to 'green distribution' [20,21], from 'green technologies' to 'green institutions' [22,23], from "green development" to "green civilization" [24,25], the concept of green development has gradually been integrated into the political sphere and has played an important role in promoting the 'greening' of the platforms of ruling parties around the world. Although research on green development and ecological civilization has developed rapidly in recent years abroad, a systematic theoretical system has not been formed for green development, and theories, such as green economy and ecological civilization, are uncertain in foreign countries, with no mature experiences and models, and insufficient academic research.

In China, as the pioneer of research on "ecological civilization", Ye Qianji developed the notion of "China's ecological civilization" as early as 1987 at a national seminar on "How to realize ecological development of agriculture" and related issues. He conducted an in-depth study of related concepts and published in his book "Ecological Agriculture: The Future of Agriculture" [26]. The book discusses the direction of agricultural development in the context of China's national conditions and focuses on the theory of ecological agriculture with Chinese characteristics. After the Party and government continuously improved the relevant concepts, the 18th Party Congress formally put forward the concept of ECC, with the principle aims of promoting sustainable development, to plant trees for future generations to "take advantage of the cool", and not deprive future generations of resources and ecological heritage [27]. The ECC is an important component of Chinese socialism, closely linked to the welfare of the populace, the nation's future, the "two hundred years" goal, and the Chinese aspiration to realize the great rebirth of the Chinese nation. Meanwhile, UGD serves as the core and pillartion and the fundamental principles of socialist core values, highlighting that UGD is a vivid practice and detailed carrier of the ECC [28]. As a result, the two have an interactive coupling relationship. In recent years, many scholars have begun to pay attention to the relationship between UGD and ECC. The relevant research mainly includes the following three aspects: first, exploring the connotation theory of UGD and ECC [29]; the second is to construct an indicator system for UGD and ECC, and comprehensively evaluate it using entropy weight TOPSIS method [30,31], analytic hierarchy process [32,33], and comprehensive evaluation method [34]; the third is to reveal the coupling and coordination relationship between UGD and ECC [6,35,36]. However, there are two areas where the current research needs to be strengthened. When it comes to indicator choice, there are relatively few studies that have quantitatively examined the relationship between UGD and ECC from an integrated system of economic, social, cultural, and environmental perspectives. Meanwhile, UGD is a multidimensional process involving economics, production, and life [37–39]. Prior research has typically concentrated on a single aspect of UGD while neglecting other socioeconomic and other indicators, making it more challenging to determine the level of UGD. Most studies have concentrated on the qualitative effects of UGD on the ECC, primarily studying the relationship from a social science perspective, excluding the spatial and temporal characteristics, and collaborative coupling between UGD and ECC. This makes it difficult to study the inner workings of UGD and ECC. The coupled coordination degree model (CCDM) has been previously used extensively to describe the overall effectiveness and coordination effects between composite systems. However, it cannot be used to look at how these two horizontal systems affect each other and how they change over time from the perspective of spatio-temporal heterogeneity. Therefore, a spatio-temporal model needs to be introduced to analyze specific influencing factors.

According to Tobler's first law of geography, any geographic feature or property is connected to others in space [40]. Modifications to the local spatial attributes will considerably affect the neighborhood. To avoid bias in the model assessment results, it is crucial to account for spatial dependence when examining the impact mechanisms [41]. Prior exploration of the influencing factors of ECC has not considered that the components of ECC are interrelated and influenced by economic development, environmental protection, and urban construction, and have shown pronounced spatial spillover effects [30,42,43]. Meanwhile, in the UGD process, production inputs, such as labor, industry, and capital, are transported between areas, which indicates that the creation of local ecological civilization may be influenced by the green growth of neighboring cities. Currently, scholars have recognized this issue and have considered spatial non-stationary correlations based on ordinary least squares (OLS) regression. GWR models are used to effectively reflect the spatial relationships between various variables by establishing local regression equations, which can provide positional guidance for decision making [44]. However, variations in how economic growth and urban infrastructure development affected the degree of ECC at various stages of UGD have also been identified [45,46]. This has indicated that the relationship between UGD and ECC fluctuates over time; indeed, time is a key factor that cannot be disregarded. To this end, this paper utilizes a spatio-temporal geographically weighted model (GTWR) that takes into account the temporal factor in order to better explain the potential relationships between UGD and ECC variables from the perspective of spatio-temporal heterogeneity, which greatly improves the accuracy of model simulations.

This study has examined the spatio-temporal variability among UGD and ECC of cities in the Yangtze River Delta area (YRD) from 2010 to 2019 by coupling CCDM and GTWR models. The following two factors led to the YRD being chosen as the study region: ① Given the YRD's increasing population density and resource exploitation intensity, the government has accelerated urbanization through high levels of industrial development to meet the requirements of economic growth. This has exceeded the YRD's ecological and environmental carrying capacity, resulting in numerous ecologic and environmental problems. Therefore, policymakers face a new task in determining how to balance the relationship between urban expansion and environment conservation. ② The YRD is an important birthplace of Xi Jinping's idea of ecological civilization, and the core value of "green water and green mountains are golden mountains" is deeply ingrained in people's hearts. The YRD has a dense network of water and rich ecosystem types, with mountains, water, forests, fields, lakes, and seas complementing each another. The natural ecological environment is one of the main components of the national policy for integrated and sustainable development of the YRD. Green and environmentally friendly development is the key solution for the YRD integration's outstanding natural ecological environment concerns, and to promote high-quality and long-term development of the regional economy.

There are two main innovations in this study. ① Methodological innovation: A new GTWR approach has been developed to investigate the interaction of UGD and ECC. This not only successfully extends the range of applications for GTWR, but also considers the relevance, diversity, and spatio-temporal heterogeneity of UGD and ECC. ② Perspective innovation: unlike prior qualitative research that has only concentrated on the political and value importance of UGD's impact on the ECC, this study used CCDM to investigate the coupled and coordinated interaction between UGD and ECC from a quantitative perspective of composite systems. The main contributions of this paper are as follows: ① The main influencing factors of UGD and ECC in the YRD region are analyzed, on the basis of which a comprehensive evaluation index system of UGD and ECC is constructed. ② Combining CCDM and the entropy-weighted TOPSIS method, a coupled and coordinated relationship model of UGD and ECC is proposed. The entropy-weighted TOPSIS method is able to evaluate the indicator data objectively and effectively avoid the errors brought by the evaluation of subjective factors. ③ Based on the GTWR model, the spatio-temporal heterogeneity of UGD and ECC in the YRD region is analyzed, which helps to identify the intrinsic correlation mechanism between UGD and ECC, put forward policy recommendations to promote green development and ecological civilization in cities in the YRD region, and provide a basis for policy makers to realize the high-quality development of ecological cities.

2. Study Area, Data Sources, and Conceptual Framework

2.1. Study Area

The YRD is a natural geographical area comprising of a delta progressively generated by the Yangtze and Qiantang rivers interacting with the sea [47]. The area includes 41 prefecture-level cities in Anhui, Jiangsu, Zhejiang, and Shanghai, the location map of the study area is shown in Figure 1. The YRD encompasses approximately 358,000 square kilometers, accounting for 3.7% of China's national territory. By the end of 2019, the population size accounted for 6% of the entire population, and the economic size represented 25% of the country's total economic volume. This has made it one of China's regions with the most integral capabilities, the highest level of population density, and the most developed economy. However, given the high population density of the YRD, intensive resource use, and level of urbanization, the natural biological environment there faces a number of regional and structural issues. The YRD and Huai River watershed systems have not been sufficiently protected, and relatively intact ecological space has been occupied in some areas. Environmental risks and hidden dangers are prominent from the petrochemical industry present along the rivers. The total resource and energy costs and pollutant emissions in the region are high, air quality indicators have not been met, and the pressure from peak greenhouse gas emissions is excessive.

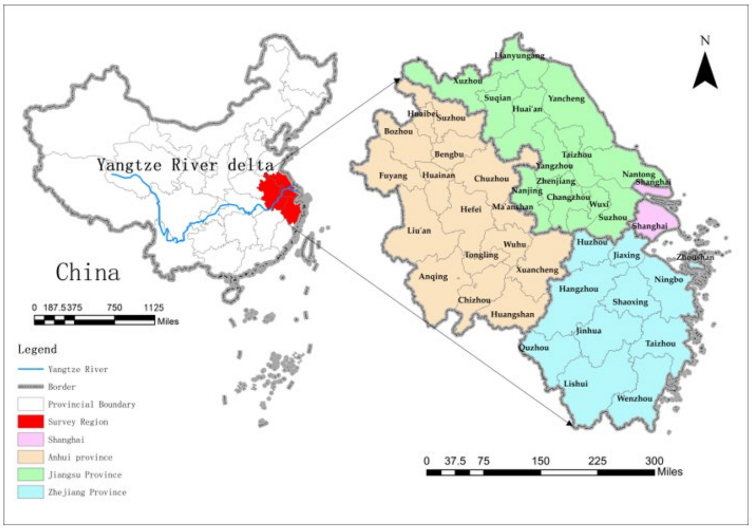

Figure 1. Location map of the study area. Note: this map is based on the standard map with the approval number GS(2020)4619 downloaded from the standard map service website of the Ministry of Natural Resources, and the base map has not been modified.

2.2. Data Sources

The data presented in this study have drawn on panel data from 41 local administrative regions in the YRD from 2010 to 2019. Panel data were derived from national, provincial, and municipal government statistical yearbooks, such as the *China City Statistical Yearbook*, *China Regional Economic Statistical Yearbook*, *Anhui Statistical Yearbook*, and the *Jiangsu Statistical Yearbook*, *Zhejiang Statistical Yearbook*, as well as statistical bulletins on each city's social development. Some missing data could be supplemented with the help of least squares or numerical smoothing. Considering the different positive and negative directions and unit magnitudes of each basic index data, before analyzing the data, it was necessary to standardize the raw data using the formula for positive index standardization (1) and the formula for negative index standardization (2) with the following formulas:

$$b_{ij} = \frac{a_{ij} - a_j^{min}}{a_j^{max} - a_j^{min}} \quad (1)$$

$$b_{ij} = \frac{a_j^{max} - a_{ij}}{a_j^{max} - a_j^{min}} \quad (2)$$

where b_{ij} is the standardized value and a_{ij} is the ith value of the jth indicator; a_j^{max} and a_j^{min} are the maximum and minimum values of the j indicators.

2.3. Conceptual Framework

There is a complex interaction between UGD and ECC. Ecological civilization and UGD are two dimensions of sustainable development, both of which have been proposed in response to the real dilemmas faced by people, such as resource depletion, energy shortage, global warming, ecological environment deterioration, and urban ecological pollution. The ECC solves the problem at the ideological and strategic levels, and UGD solves the problem at the level of strategic measures. This is ultimately implemented and developed through the combination of people, industry, and economy. Promoting a life in tune with nature is the most important aspect of promoting China's ECC. It is crucial to deal with the peaceful coexistence of people and nature, solve outstanding environmental problems with a value-based approach, promote the steadfast fight against pollution, increase the effectiveness of resource allocation, and raise the bar on urban development quality to guarantee sustainable development of the national economy and society. A strategic step toward achieving ECC, green and sustainable urban development is also an unavoidable decision for ecological civilization. The first aim of UGD is strategic and scientific green urban planning. This is then followed by improvement and optimization of green industrial structures and, ultimately, green technical innovation. Fundamentally, effective management of the relationship between humans and nature is the issue that ecological civilization and UGD are meant to tackle. Human lifestyles will influence the natural ecological environment because humans are a part of nature. As a result, we need to develop basic ideals on how to live in harmony with nature, observe natural laws, and safeguard natural resources. Industrial growth is regarded as an essential engine of urban expansion, with considerable implications for the natural biological environment. In this process, it is necessary to establish a sense of "ecological rationality" and consciously consider the ECC as a strategic guiding ideology. UGD should combine the elements of space, new energy, new industry, new technology, new themes, and other elements organically. This then promotes the black industrial development mode of "overspending resources and destroying the natural ecological environment" to transform into the green sustainable development choice mode. The transformation, coupling and coordination of multiple elements of "people–industry–economy" enable cities to achieve green growth in the economic system, increase green wealth in the industrial production system, and further enhance green welfare in the social life system. Determining the coordination relationship and internal workings of UGD and ECC can therefore support the development of effective policies for high-quality urban development in a conceptual framework, as shown in Figure 2 below.

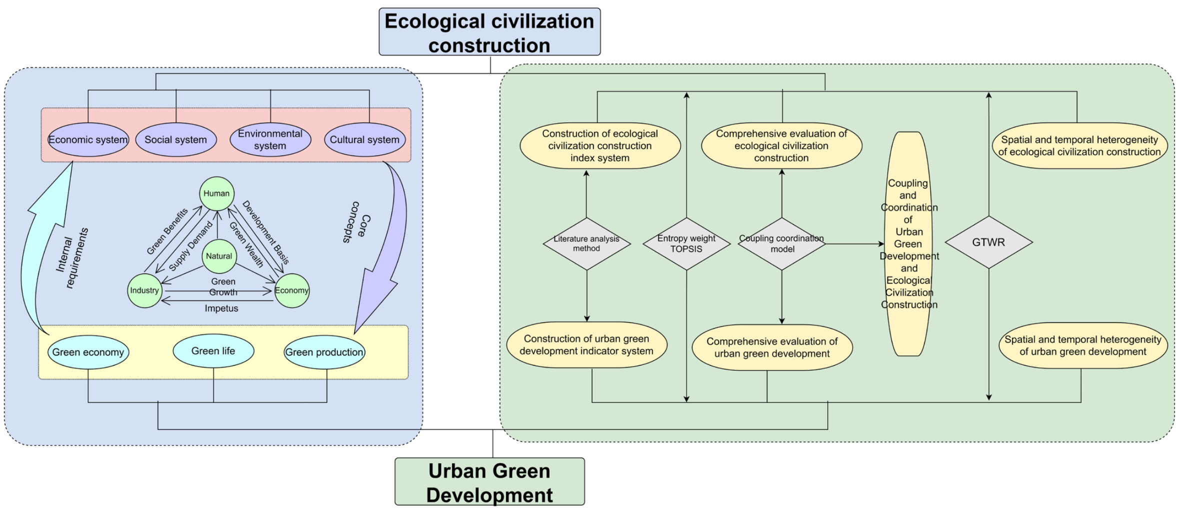

Figure 2. Main research methods and processes.

3. Research Methodology

The following steps make up the research methodology and main procedure employed in this article, which are depicted in Figure 2. ① Appropriate assessment indicators for UGD and ECC are studied through a literature analysis method. ② The comprehensive evaluation index of UGD and ECC was calculated using the entropy-weighted TOPSIS approach. ③ The degree of coupled coordination among UGD and ECC within YRD prefecture-level cities was examined using the CCDM. ④ Based on the GTWR model to explore the spatio-temporal heterogeneity among UGD and ECC. Here are some specific research methods:

3.1. UGD and ECC Evaluation: Based on an Entropy-Weighted TOPSIS Method Measure

3.1.1. Indicator System Construction

The foundation for understanding the coupled and coordinated relations between the ECC and UGD is the scientific and thorough creation of the related evaluation index system.

The evaluation index of ECC predominantly refers to the National ECC Assessment Target System (revised in 2016) and draws on existing research results [13,15,48–51]. It combines the characteristics of the YRD, according to the systematic, representativeness and usability principles. The ECC is divided into the four primary indicators of the economic system, cultural system, social system, and the environmental system. A total of 20 secondary indicators, such as the rate of forest cover and urban population density, are used to construct an index system for measuring the ECC level in the YRD. The evaluation index of ECC is used to characterize the ECC level of each prefecture-level city in the YRD. The UGD evaluation index system mainly refers to the UGD evaluation indices in the National Green Development Index System (revised in 2016). It also draws on other relevant research results [14,37,38,52,53] from the green economy, green production, and green life. The 16 indicators, such as the proportion of employees in the secondary industry and industrial wastewater emissions, were selected from three first-level indicators to construct a detailed evaluation index for UGD to characterize the UGD level of each city at the prefecture level in the YRD. Because there may be multicollinearity among the variables selected according to a literature review, this paper uses variance expansion factor (VIF) to analyze multicollinearity of all variables before spatial econometric analysis. The results show that the VIF of all variables is less than 10, so there is no multicollinearity between variables, and regression analysis can be carried out. The operability and accessibility of index data were taken into consideration when building the coupled and coordinated assessment index system of UGD and ECC in the YRD, as shown in Table 1.

Table 1. Coupled and coordinated evaluation index system of ECC and UGD in the YRD.

Primary Index	Secondary Index	Three-Level Index	Unit	Characteristic	Weights	VIF
ECC	Economic System	GDP percentage for the tertiary sector	%	+	0.029	3.41
		Energy usage as a percentage of GDP	Ton of common coal for every million yuan	–	0.013	1.749
		Fiscal revenue as a share of GDP	%	+	0.041	1.55
		Income available per person in urban households	Yuan	+	0.048	4.38
		Rural dwellers' disposable income per capita	Yuan	+	0.051	2.103
	Cultural System	Number of students registered at institutions of higher learning in general	People	+	0.124	2.047
		Public library book collection	Thousands of copies, pieces	+	0.198	6.473
		Number of full-time teachers in higher education	People	+	0.140	3.562
		Education spending as a share of GDP	%	+	0.044	1.172
	Social Systems	Urbanization rate	%	+	0.028	2.941
		Urban population density	(People/km^2)	–	0.006	2.128
		Number of doctors (practicing physicians and practicing assistant physicians)	People	+	0.066	2.496
		Urban medical insurance coverage rate	%	+	0.044	2.461
		Urban pension insurance coverage	%	+	0.043	1.215
		Urban Engel coefficient		–	0.018	1.902
	Environmental Systems	Coverage of forests	%	+	0.063	1.199
		Greening coverage of built-up areas	%	+	0.016	1.065
		Industrial wastewater discharge	Million tons	–	0.009	3.895
		Comprehensive use rate for general industrial solid waste	%	+	0.009	1.077
		Industrial sulfur dioxide emissions	Ton	–	0.008	4.209

Table 1. *Cont.*

Primary Index	Secondary Index	Three-Level Index	Unit	Characteristic	Weights	VIF
Urban Green Develop-ment	Green Economy	The percentage of personnel in secondary industry	%	–	0.05	7.574
		The percentage of workers in tertiary industry	%	+	0.05	6.75
		Total labor productivity	10,000 Yuan/person	+	0.04	1.111
		Food crop production	Million tons	+	0.11	1.061
		Retail sales of social consumer products	Billion	+	0.18	1.036
	Green Living	Resident population	10,000 people	–	0.01	2.471
		Green space per capita	m^2	+	0.10	6.754
		Road area per capita	m^2	+	0.10	5.425
		Sewage treatment rate	%	+	0.03	1.217
		Garbage disposal rate	%	+	0.02	1.182
		Share of urban construction land	%	–	0.01	3.398
	Green Production	Discharge of industrial wastewater	Million tons	–	0.01	7.01
		Industrial emissions of sulfur dioxide	Ton	–	0.02	4.333
		Emissions of industrial fumes	Ton	–	0.03	1.915
		Investment in environmental management as a percentage of GDP	%	+	0.09	1.181
		Patent for inventions in the environmental protection industry	Piece, individual	+	0.16	4.926

3.1.2. Entropy Power TOPSIS Method

The entropy-weighted TOPSIS approach combines the entropy-weighted method and the TOPSIS method to provide a full examination of the fundamental indicators. When measuring the system of comprehensive evaluation indices, the subjective assignment method and the objective assignment method are the most common methods used to determine the weight index system. The entropy TOPSIS method belongs to the objective assignment method. The indicators were objectively weighted based on the degree of variation in each indicator value to avoid the influence of subjective factors, calculating the distance between each appraisal method and the best and worse scheme. The relative overlap between each evaluation scheme and the best scheme was then determined, and finally the evaluation schemes were ranked. The indicator weights and the final evaluation indices were calculated from the indicators. The evaluation outcomes were improved by using the entropy weight TOPSIS approach, and the specific calculation methods are as follows.

① Building a standardized matrix:

$$A = (a_{ij})_{m\times n} \tag{3}$$

where a_{ij} represents the data after normalization.

② Determine the entropy of evaluation indicators:

$$\begin{aligned} f_{ij} &= a_{ij}/\sum_{i=1}^{m} a_{ij} \\ H_j &= -\frac{1}{\ln m}\left(\sum_{i=1}^{m} f_{ij} \times \ln f_{ij}\right) \end{aligned} \tag{4}$$

where f_{ij} denotes that the first j indicator in the first i; the weight of the indicator in the first program, and the weight of the indicator in H_j denotes the entropy value of the j the entropy value of the indicator.

③ Calculate the entropy weight of the index:

$$w_j = (1 - H_j) / \sum_{j=1}^{n} (1 - H_j) \quad (5)$$

where w_j denotes the first j weight of the indicator.

④ Calculation of weighted evaluation weights:

$$R = (r_{ij})_{m \times n}, \text{ where } r_{ij} = w_j a_{ij} \quad (6)$$

where r_{ij} denotes the weighted standardized index value.

⑤ Determine the optimal solution Q_+ and the inferior solution Q_-:

$$\begin{aligned} Q_+ &= (r_1^+, r_2^+, \cdots, r_n^+) \\ Q_- &= (r_1^-, r_2^-, \cdots, r_n^-) \end{aligned} \quad (7)$$

⑥ Calculate the distances of each program from Q_+ and Q_-:

$$\begin{aligned} D_i^+ &= \sqrt{\sum_{j=1}^{n} (r_{ij} - r_i^+)^2} \\ D_i^- &= \sqrt{\sum_{j=1}^{n} (r_{ij} - r_i^+)^2} \end{aligned} \quad (8)$$

⑦ Calculate the evaluation index of each program:

$$C_i = \frac{D_i^-}{D_i^- + D_i^+} \quad (9)$$

where $C_i \in [0, 1]$, and the higher the score of the city C_i, the higher the level of green development and ECC of the city.

3.2. Coupled Coordination Degree Model (CCDM)

The coupling degree is a concept that originates from physics but has wide application in other research fields given the relatively similar coupling links between systems. It works by analyzing how closely two or more systems interact and are coupled, which establishes an ordered trend in integrated systems. The degree of coupling (Formula (10)) and the degree of coupling coordination (Formulas (11) and (12)) were used in this study to measure and assess the degree of coordination between the UGD and ECC and its subsystems. The following are the specific models:

$$C = \sqrt{(U_1 \times U_2) / ((U_1 + U_2)/2)^2} \quad (10)$$

$$T = \alpha U_1 + \beta U_2 \quad (11)$$

$$CD = \sqrt{C \times T} \quad (12)$$

where C stands for the level of coupling between the UGD and ECC, T represents the overall evaluation index, and CD represents the level of coupling coordination between the UGD and ECC. The comprehensive indices of UGD and ECC are denoted by the letters U_1 and U_2, respectively. Given that these two subsystems are equally crucial for determining the level of coordination amongst UGD and ECC, they are both assigned the same weight, or 0.5 [54]. In this study, referring to the classification of coordination types in the related research literature [4,55], the coupling coordination types of UGD and ECC are classified into four categories on the basis of the magnitude of the coupling coordination degree CD, that is, when $0 < CD \leq 0.3$, it indicates no correlation. When $0.3 < CD \leq 0.5$, it indicates a low degree of correlation, when 0.5 < $CD \leq 0.8$, it indicates primary coordination, and when 0.8 < $CD \leq 1$ indicates quality coordination.

3.3. Space–Time Weighted Regression Model (GTWR)

Wang et al. [56] highlighted that "although geographically weighted regression (GWR) models can deal with spatial heterogeneity and detect spatially varying patterns of relevant variables, they do not directly consider spatial dependence, and their residuals are uncertain". The spatio-temporal GTWR proposed by Huang Bo et al. [57] incorporates the spatio-temporal characteristics of the data into the regression model based on the GWR model, that is, it incorporates spatio-temporal distances and constructs (X,Y,T), and three-dimensional coordinates, which can simultaneously consider the effects of spatio-temporal distances on each explanatory variable. As a result, the spatio-temporal variability among UGD and ECC was examined in this article using the GTWR model in the following manner:

$$Y_i = \beta_0(\mu_i,\ v_i,\ t_i) + \sum_{k=1}^{p} \beta_k(\mu_i, v_i, t_i) X_{ik} + \varepsilon_i; i = 1, 2, \ldots, n \tag{13}$$

where Y_i is the value of the explanatory variable for the ith city, n is the number of cities in the YRD, and k is the number of explanatory variables for the ith city; t_i is the temporal coordinate of the ith city. $\beta_0(\mu_i, v_i, t_i)$ denotes the spatio-temporal intercept term for city I; X_{ik} denotes the value of the kth explanatory variable for city I; $\beta_k(\mu_i, v_i, t_i)$ denotes the regression coefficient of the kth explanatory variable for city I as a function of the spatio-temporal coordinates; and ε_i is the error term.

4. Analysis of Results

4.1. Analysis of the Spatial and Temporal Evolution Pattern of UGD and ECC

4.1.1. Time Evolution Pattern Analysis

Since the YRD's regional integration strategy was upgraded to a national stratagem in 2018, emphasizing ecological protection and promoting a green economy as a priority for cities in the YRD, and enhancing economic development, industrial production, and people's lives, the level of UGD in the YRD has shown a gradual upward trend from 2010 to 2019 (Figure 3). Since 2018, UGD has shown a rapid uptrend trend. Green economic development from 2010–2019 showed an upward trend in the early period (2010–2012), and the middle and late period (2012–2019) showed a changing trend from a stable period to a fluctuating upward trend. However, it was always maintained at a low level. Green production development has shown a fluctuating upward trend from 2010–2018, fluctuating even more in this time period in the technology mapping stage. After 2018, city green development with an upward trend has shown that green production can promote UGD. Green living as a whole shows a declining trend. The reason is that from 2005–2015, due to the YRD region's vigorous development of urban economy resulting in extremely rapid population growth, the population density grew too fast and the urban infrastructure construction could not meet the negative impact brought by the rapid population, so green life as a whole showed a decreasing trend from 2010–2019, but green life was always at a higher level, indicating that green life provides a strong impetus to UGD. This demonstrates that in the early stages of green city development in the YRD (2010–2017), when UGD was relatively slow, it was in the exploration stage. In the later stages of green city development (2018–2019), green production development and green living development gradually took over as the primary driving forces for the UGD.

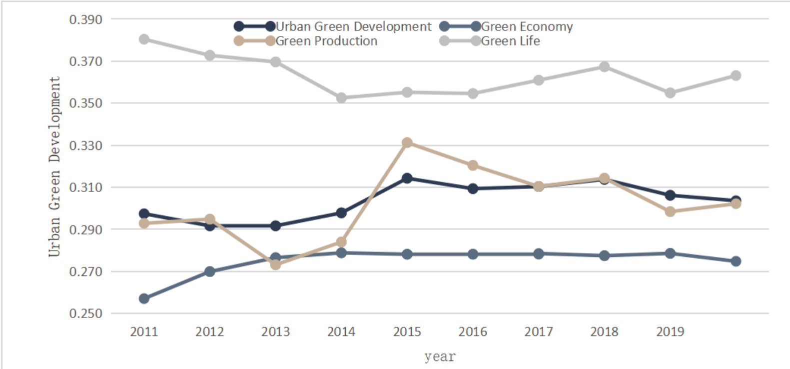

Figure 3. Temporal evolution pattern of UGD.

Figure 4 shows the trends of ECC and its four subsystems in the YRD from 2010 to 2019, in which the level of ECC shows a slow upward tendency. The level of ECC has progressively improved during this time, as shown by the increase in mean ECC value from 2010 to 2019 and from 0.235 to 0.268 in 2019. The trend of environmental system change has shown a slow decline followed by a fluctuating increase. This has indicated that since 2013, The YRD has improved environmental protection efficacy and supported the advancement of ecological civilization level. The similarities between the change patterns of the economic and cultural systems and those of the ECC have shown that these two systems are crucial to the process of enhancing the ECC. Building the social system is crucial in advancing ECC given that it was in a rapidly increasing trend prior to 2014. However, it remained relatively constant after 2014 and always remained at a relatively high level. This has shown that the lives of people in the YRD have generally been maintained at a high level.

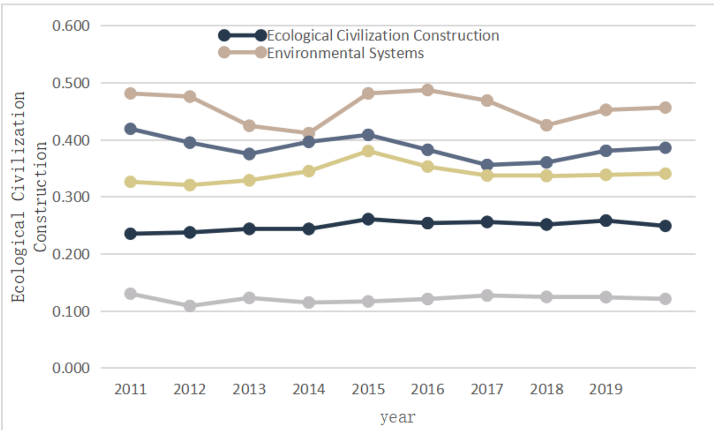

Figure 4. Temporal evolution pattern of ECC.

4.1.2. Analysis of the Spatial Evolution Pattern

Figure 5 shows the spatial framework of UGD in the YRD in 2010, 2015, and 2019. The cities with a higher green development level in 2010 were Nanjing, Suzhou, Hangzhou, and Shanghai, among which Shanghai has the highest level of 0.63. The western inland region of the YRD is where most of the cities with a lower level of green development are located. Among these, Lu'an has the lowest level of 0.18, indicating that there was a severe bifurcation of the UGD level among the cities in the YRD. In 2019, the UGD level in the high development zone comprising Nanjing, Wuxi, Shanghai, and neighboring cities, is still higher than that in other regions of the YRD. Shanghai scored the highest, at 0.63, followed by Wuxi and Nanjing, both of which scored 0.48. Huainan City, which had the lowest score of 0.19, is in the low UGD zone, which is primarily in the northwest of the YRD. This has shown that over the last ten years, the central–eastern cities in the central–eastern region have shown more rapid green development. Overall, from 2010–2019, the level of UGD in the YRD was on an upward trend, but there were pronounced regional differences. ① With a high degree of UGD and a potent siphon effect, the eastern area, concentrated in Shanghai, Wuxi, and Nanjing, attracts top-notch technical personnel and market resources from the YRD. ② Most of the central region's cities, with Hefei, Wuhu, and Hangzhou serving as the region's hubs, are at a middle to high degree of green development. Their growth is aided by the "edge effect" of the metropolis. The center cities' ability to cluster green development has improved and their growth potential has increased more rapidly with integrated development of the YRD. ③ The northwestern part of the YRD is further away from the high growth urban agglomeration, and, therefore, the UGD was relatively slow.

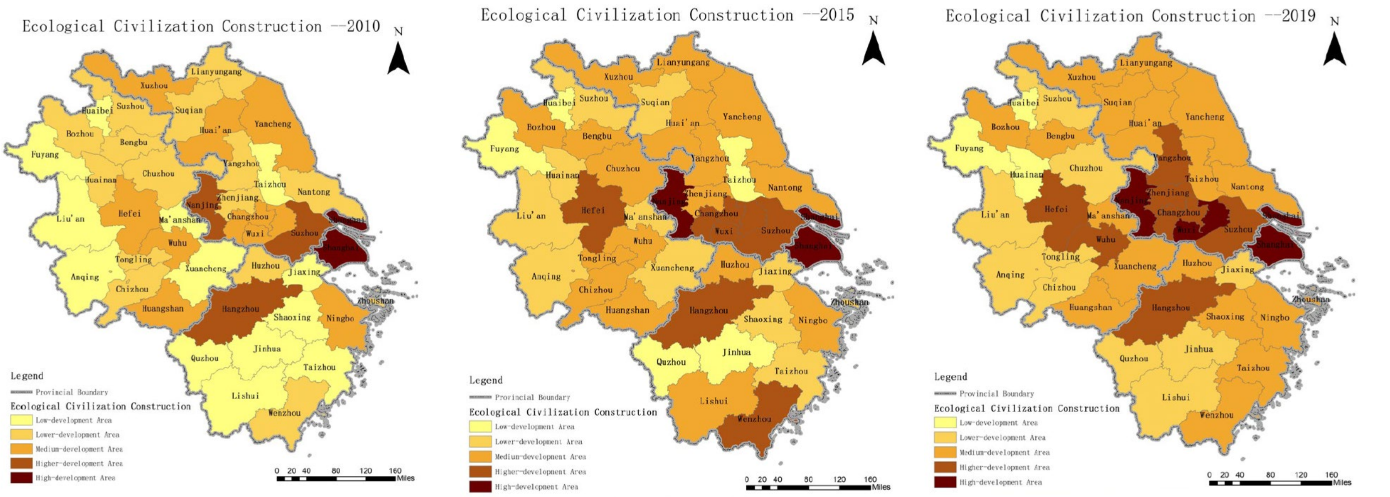

Figure 5. Spatial evolution pattern of UGD.

Figure 6 shows the spatial pattern of the level of ecological civilization in the YRD in 2010, 2015, and 2019. From 2010–2019, the overall ECC level is in a transitional pattern, with Nanjing, Shanghai, and Hangzhou forming three high level zones. This has then driven the development of ECC in surrounding cities to transition outward and drive the development of ECC in the YRD. From the perspective of provincial administrative regions, the level of ECC in the YRD is Shanghai > Zhejiang Province > Jiangsu Province > Anhui Province. In the three time cross-sections, in 2010, there are 23 cities in the lower level and low-level zone, accounting for 56.1%, which were predominantly concentrated in the northern part of the YRD. There were 13 cities in the middle level zone, accounting for 31.7%, which were mainly concentrated in the southeastern part of the YRD. There were five cities in the higher level and high-level zone, accounting for 12.2%, primarily in the region's central–eastern portion. In 2019, the number of lower level and low-level cities gradually decreased to 17, accounting for 41.5%, which were mainly concentrated in the northwest inland region. The number of medium level cities decreased to eight, accounting for 19.5%. Higher level and high-level cities accounted for 36.6%, an increase of 24.4% from 2010, which were mainly concentrated in the southeast coastal region. Figure 7 shows that the level of ecological civilization has had a more pronounced increase in the cities around Shanghai, Hangzhou, and Nanjing. Meanwhile, the cities further away from them have improved more slowly. The UGD and ECC level was positively correlated and the higher the level of UGD, the higher the level of ECC in cities. In terms of spatial distribution, the UGD and ECC of cities in the southeast coastal territory was more elevated than that of the entire northwest inland territory.

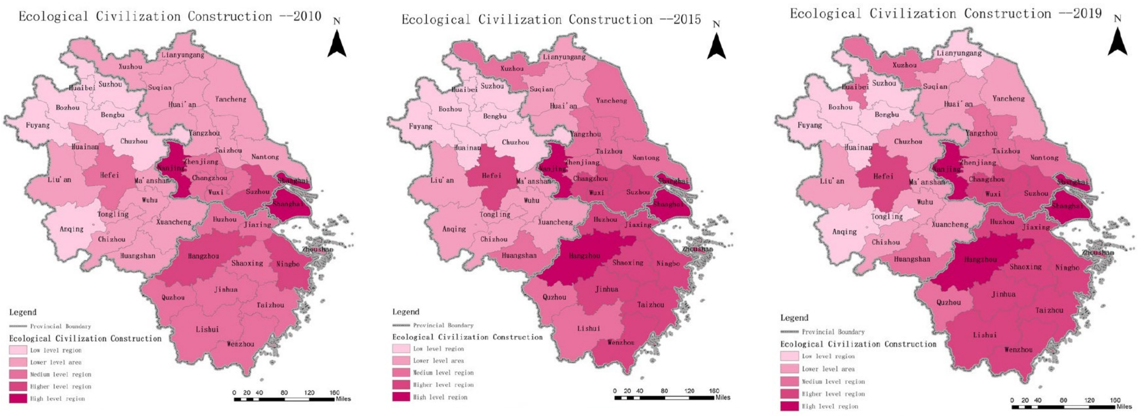

Figure 6. Spatial evolution pattern of ECC.

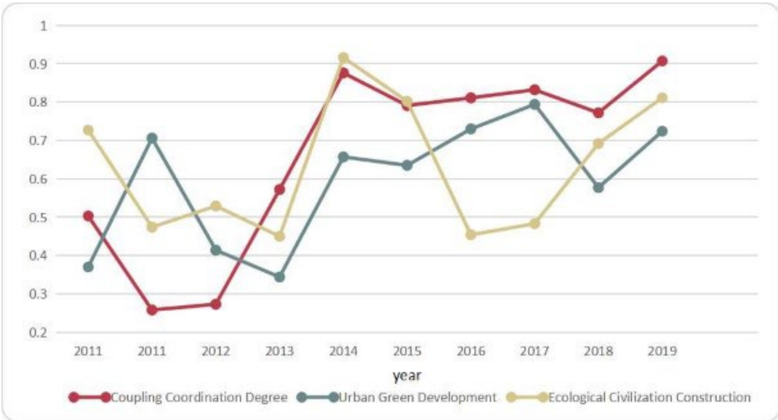

Figure 7. Temporal trend of coupling coordination.

4.2. Coupling and Coordination Analysis of UGD and ECC

4.2.1. Temporal Trends of Coupling Coordination

The degree of coordination of UGD and ECC in the YRD from 2010 to 2019 was measured using a coupled coordination degree model, and its development type was analyzed. Figure 7 shows that the degree of UGD in the YRD increased from 0.37 in 2010 to 0.724 in 2019. The degree of ECC increased from 0.727 in 2010 to 0.811 in 2019, and the degree of coupling coordination continued to increase from 0.503 in 2010 to 0.907 in 2019. All three of these indicators have been rising and fluctuating over the last ten years. This has shown that the level of collaboration between green development and ECC in cities in the YRD is still in the exploratory stage and is likely to improve in the future. A further indication that national policies have had a substantial impact on the coordinated advancement of green cities and ecological civilization is the timing of the change in coordination type. This is compatible with the point in time of China's 13th Five-Year Plan. The early stage of UGD (2010–2013) was in the exploration stage, when the UGD trend was more volatile and the impact on the ECC was at a lower level of coordination with the ECC. During this, many researchers compared the UGD situation in China and internationally and developed an UGD path applicable to China's national conditions [58–60]; the middle and late stage of UGD (2013–2019) belongs to the stage of fluctuation and rise, proposing "fostering green sustainable growth and constructing a beautiful China", when the road to UGD has become mature, and the influence and coordination of ECC have been greatly enhanced. However, the level of ECC dropped substantially because of strengthening of environmental protection. This has led to the increase in enterprise investment in pollution control, including measures such as shutting down production and rectification. Although the UGD and ECC coordination degree spans four stages from 2010 to 2019, the degree of coupling coordination between the two systems still has not reached a high level of equilibrium. This is because there is still considerable space for improvement in the degree of coupling coordination between the two.

4.2.2. Coupling and Coordinating Spatial Patterns

The spatial distribution of UGD and ECC coordination in the YRD in 2010, 2015, and 2019 is shown in Figure 8. The YRD's general degree of cooperation has increased from 2010 to 2019. In 2010, 70.73% of the cities in the YRD were in severe dissonance and on the verge of dissonance. As of 2019, 60.97% of the cities in the YRD were in primary coordination and quality coordination. There are still substantial differences among the cities in the YRD in terms of coupling coordination. Generally, the southern YRD has a higher level of cooperation than the northern YRD, and the eastern coastline zone has a higher level of coordination than the western interior region. Analyzed from the perspective of provincial administrative regions, the order of UGD and ECC coordination is Zhejiang Province > Jiangsu Province > Anhui Province. The UGD and ECC high-level city cluster consists of Shanghai, Nanjing, and Hangzhou, and has played a key role in advancing ecological civilization and green urban development as the YRD's core region.

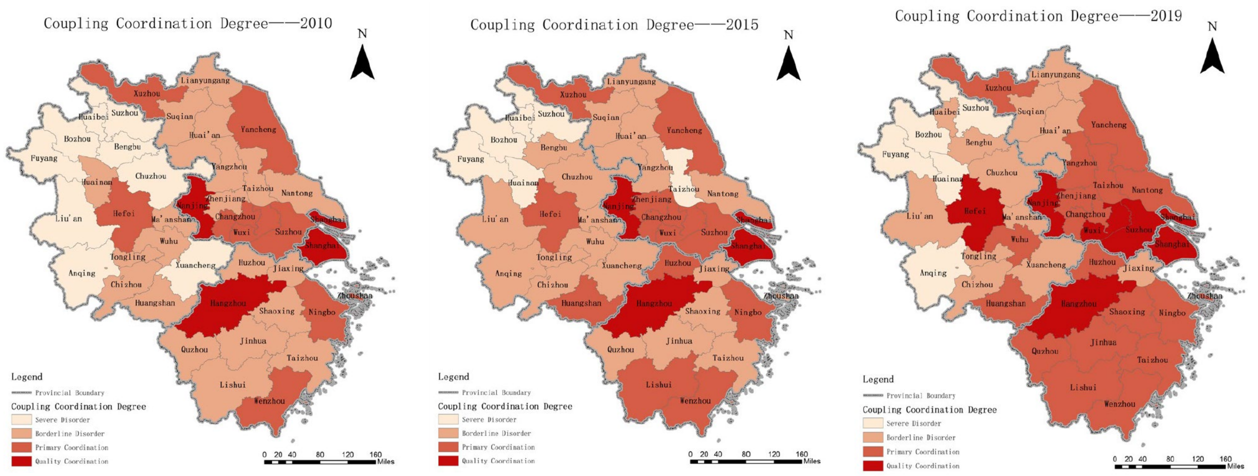

Figure 8. Spatial pattern of coupling coordination.

4.3. Analysis of Spatial and Temporal Differences between UGD and ECC

This study has examined the effects of UGD and its equipment on ECC and the effects of ECC and its equipment on UGD, from 2010 to 2019, to clarify the mechanism behind the connection between UGD and ECC. Table 2 presents the specific modeling variables and findings. All the models have a high level of explanation and can explain the link between UGD and ECC.

Table 2. GTWR model calculation results and parameters.

Dependent Variable	R2	Bandwidth	Sigma	AICc	Spatio-Temporal Distance Ratio	Residual Squares
UGD	0.933704	0.114996	0.0191119	−1810.77	0.373068	0.149758
ECC	0.970262	0.114996	0.023251	−1724.87	0.268765	0.221651

4.3.1. Time Variance Analysis

The effects of UGD and its equipment on the ECC at the timeframe are shown in Figure 9a–d. UGD gradually tends to have a positive impact on the ECC, and the intensity of that impact has gradually increased. Social life, industrial production, and economic growth have all had an impact on UGD levels, and when those levels have been reached, the ECC will improve.

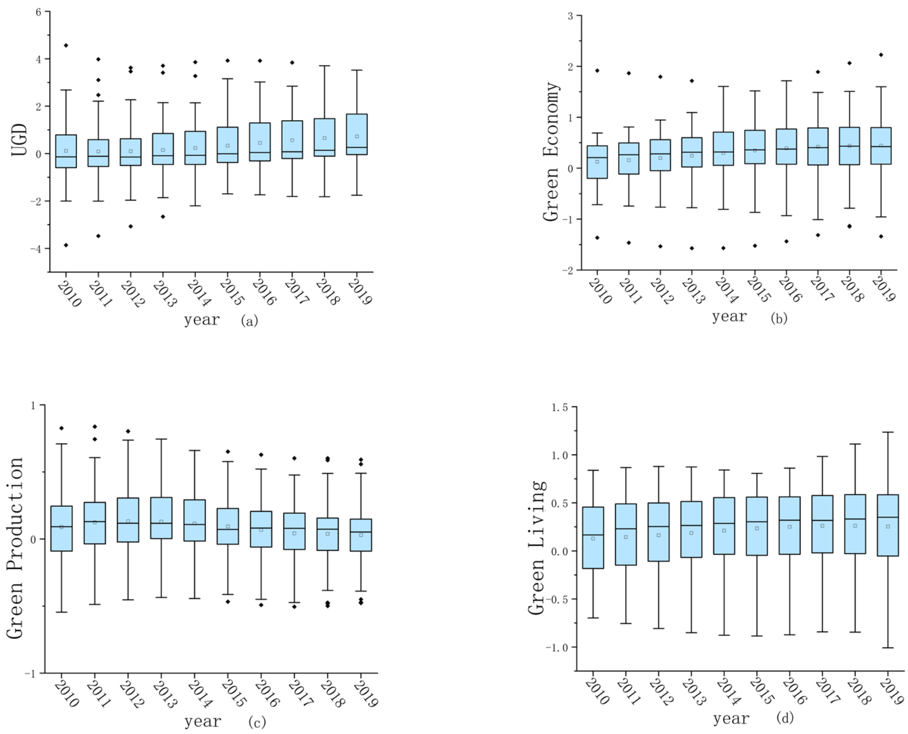

Figure 9. Analysis of the temporal variability of UGD. Where (**a**) indicates the level of influence of UGD on the ECC; (**b**) indicates the level of influence of green economy on the ECC; (**c**) indicates the level of influence of green production on the ECC; (**d**) indicates the level of influence of green living on the ECC.

① As can be seen in Figure 9b, the positive effect of the green economy on the level of ECC has shown a steady upward trend. This is primarily closely connected to government support and changes in the market environment, developing low-carbon and environmentally friendly development, promoting sustainable resource use, putting energy conservation and emission reduction efforts into practice, actively developing the circular economy, and working to create a green life production model.

② From Figure 9c it can be seen that green output has a first-rising positive impact on the level of ECC. It then falls and finally tends to stabilize the trend, predominantly because the continuous development of industrial production has driven the construction of the urban economy and urbanization level. While indirectly supporting the development of urban ecological civilization, this also serves to bolster green production and realize a society where production and ecology coexist peacefully. However, as production levels have risen steadily, they have also caused severe environmental damage and put undue strain on natural resources, lowering the level of ECC.

③ Figure 9d show that people's adoption of a green lifestyle has had a favorable impact on the level of ECC that is more consistent and on the rise. At a meeting of the Political Bureau of the 18th Central Committee of the CPC Central Committee Standing Committee in 2013, Chinese Leader Xi Jinping made an important speech in which he "advocated green lifestyle," that is, a green and sustainable way of living for people, as a means for socialist nations to promote the ECC and to steadfastly carry out the requirements of the new development concept, which is more conducive to promoting the ECC way of life.

The effects of ECC and its equipment on UGD over time are shown in Figure 10a–e. Overall, the impact of ECC on UGD has changed from negative to positive, and the intensity of the impact has gradually increased.

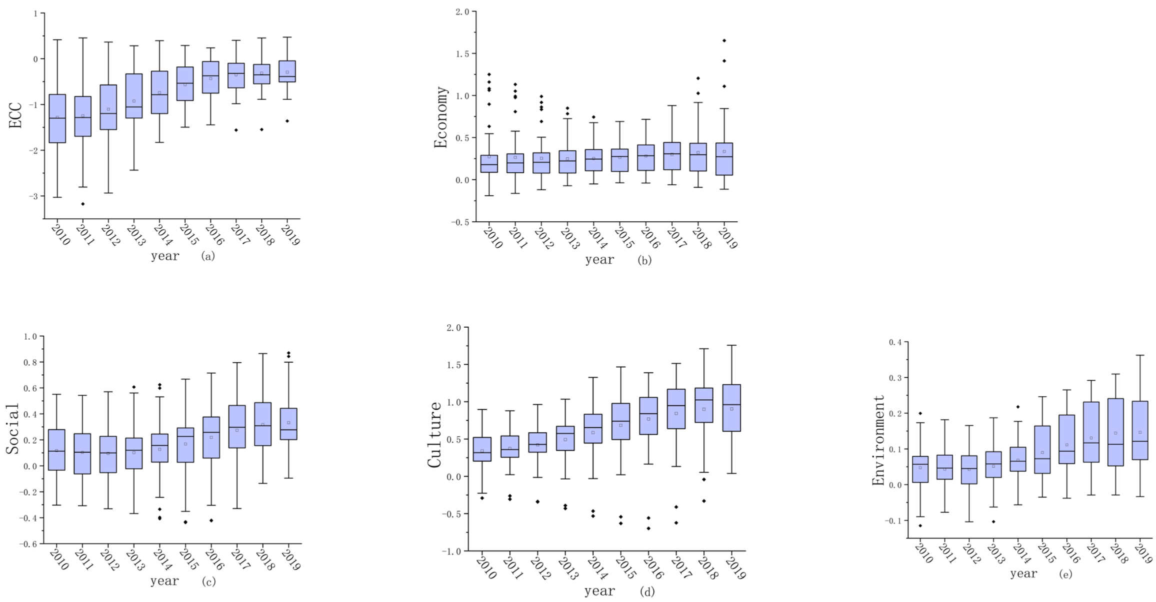

Figure 10. Analysis of the temporal variability of ECC. Where (**a**) indicates the level of influence of ECC on UGD; (**b**) indicates the level of influence of economic system on the level of UGD; (**c**) indicates the level of influence of social system on UGD; (**d**) indicates the level of influence of cultural system on UGD; (**e**) indicates the level of influence of environmental system on UGD.

① As can be seen in Figure 10b, the trend of the economic system's positive influence on UGD is upward, implying that as the economy's level of technological development rises, the strategy for developing the digital economy has been gradually optimized. As the strategic tasks for UGD have been developed and proposed, the rise in digital development of economy quickly becomes the primary influencing factor for advancing UGD. Zhu et al. (2022) noted that the digital economy has had a highly positive impact on the improvement in UGD level and has turned into an important driving force for urban green transformation, and the degree of influence is gradually increasing.

② From Figure 10c it can be seen that the social system's beneficial impact on UGD is increasing and the influence of social development on UGD declined slowly before 2013. This is because of development of urban productivity in the YRD before 2013, which caused more pressure on the environment and inhibited the speed of UGD. After 2013, China's urban economies have increasingly transitioned toward green and environmentally friendly growth. To advance the UGD process, it is vital to include the idea of ecological civilization into all facets of the urbanization development process and to follow a new low-carbon and environmentally friendly path for urban construction.

③ Figure 10d show that there has been a gradual upward trend in the positive influence of cultural systems on UGD. This is closely related to the strong government support for education schools and the development of emerging technologies. Green sustainable development of cities can be realized with the expansion and support of green culture, which generally has a positive guiding influence on this process. Without intensive cultivation of people's green cultural consciousness, sustainable urban development cannot be accomplished. The sustainable development of cities cannot be achieved without the extensive cultivation of people's green cultural awareness. To strengthen the excavation and inheritance of cultural resources, actively cultivate a green culture and implant the cultural gene of green development, so that the concept of green water and green mountains as the silver mountain of gold becomes a universal concept in today's society, further promoting the intrinsic power of green development in the city.

④ As can be seen in Figure 10e, the influence of environmental systems on UGD is similar to that of culture, both of which have an annual rising trend, was mainly related to government policies and industrial structure. Eco-environmental improvement is the fundamental driving force and necessary measure for UGD. Hu [61] has highlighted that the imbalance in the ecological environment is the fundamental cause of inhibiting UGD and restricting urban socio-economic development. As a result, in the cause of advancing the UGD process, the YRD has worked hard to enhance the ecological environment's quality by expanding investments into high-tech and green sectors.

4.3.2. Spatial Variation Analysis

The average of the yearly impact coefficients of the interactions between the UGD and ECC in the YRD from 2010 to 2019, as shown in Figures 11 and 12. The parametric results are based on the GTWR model. As shown in Figure 11, UGD has improved the level of ECC in the southeastern local-level cities in the YRD but inhibited the level of ECC in the northwestern prefecture-level cities. This has demonstrated that the level of green development varies substantially amongst some of the cities in the YRD, with Shanghai, Nanjing, and Hangzhou acting as the region's hub and outward extensions. Given the booming seaside economy, rising living standards, and the green industry's dominance of the industrial structure, the southeastern cities are growing quickly. The cities in the northwest are expanding slowly because of the slow growth of the inland economy, with heavy industry making up the bulk of the main industrial structure. This has resulted in the slow growth of the local ecological civilization. To encourage coordinated growth among UGD and ECC, it is therefore required to design various strategies in accordance with the differences in geographic location, economy, industrial composition, and urban infrastructure.

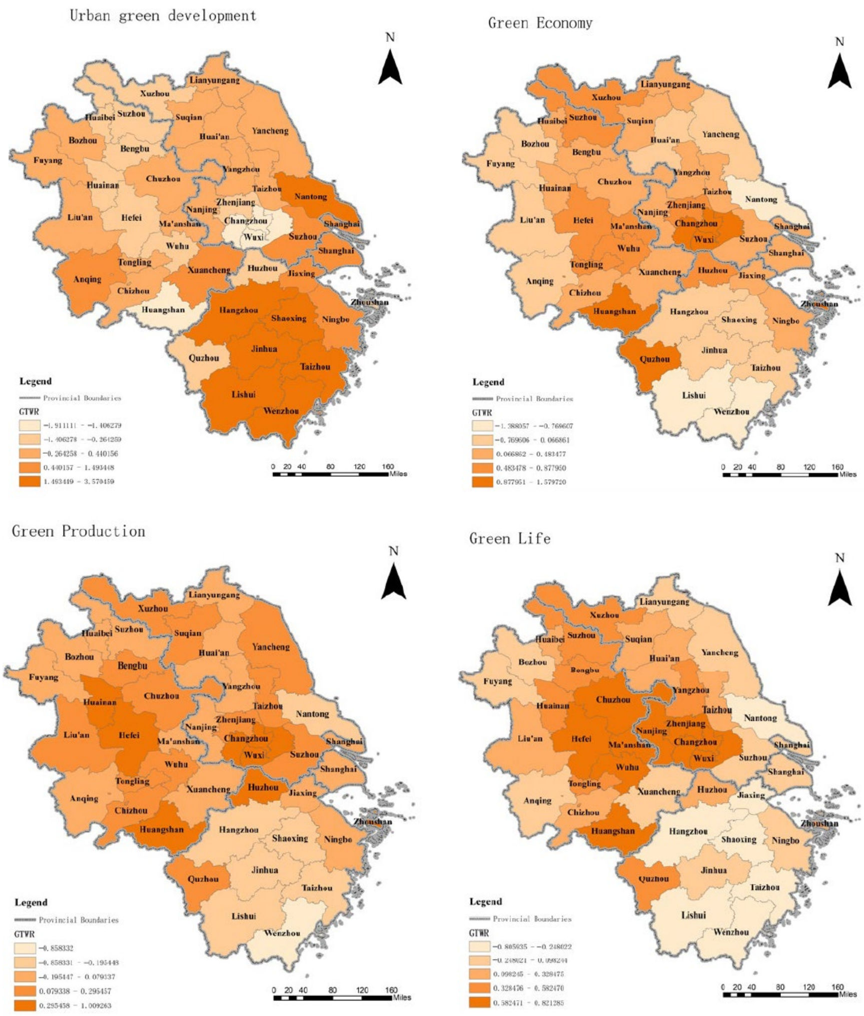

Figure 11. Spatial variation analysis of UGD.

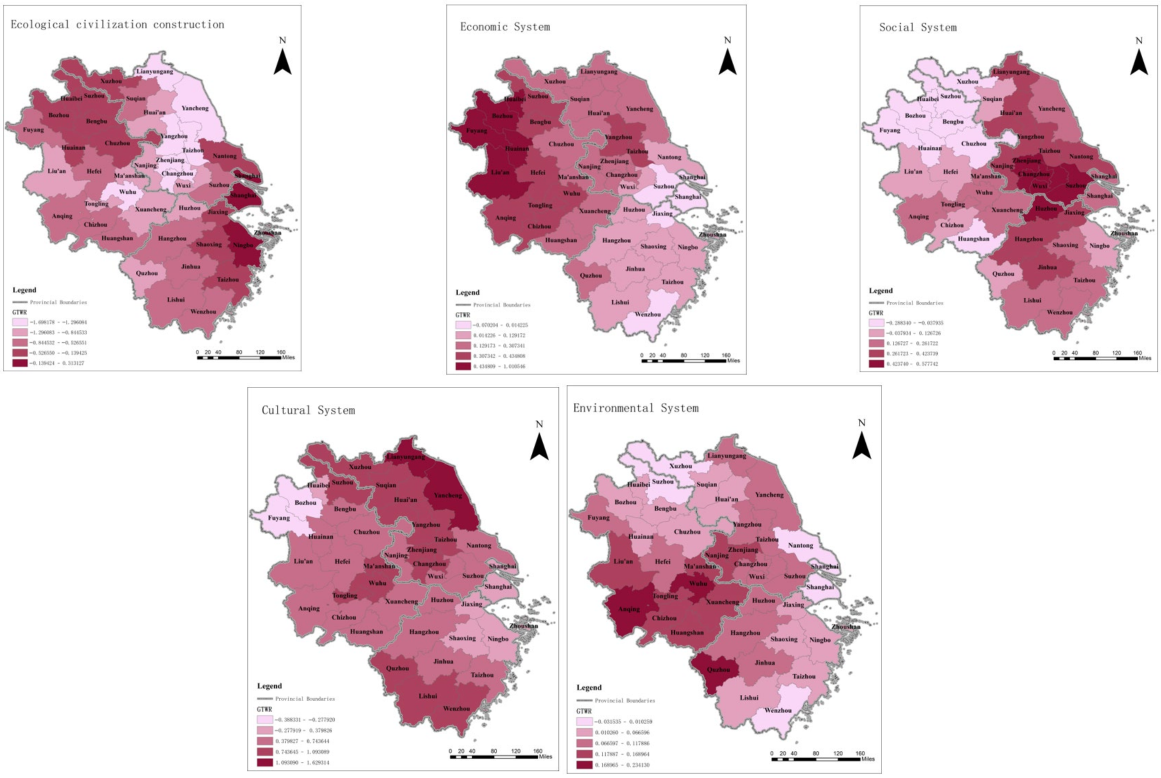

Figure 12. Spatial variation analysis of ECC.

① The level of green economic development has brought positive effects for most cities within the YRD, and only a few cities have negative regression coefficients. Huangshan City has the highest absolute value of coefficients of the level of green economic development, followed by Wuxi City, while Hangzhou City has the lowest absolute value. There are two scenarios when there is a correlation between the rate of green economic growth and the amount of ECC. In the central cities of the YRD, such as Huangshan City, Wuxi City, Changzhou City, and Quzhou City, the degree of influence of the extent of green economic progress on the extent of ecological and environmental protection is high. However, the ecological and environmental protection standards of these cities are at a low–medium level. To improve the ecological and environmental protection levels of these cities, the focus should be on improving the local level of green economic development. The extent of green economic progress, such as that of Hangzhou, which is a high level ECC area, has a low impact on the level of ECC but has a high influence on the nearby cities' levels of green economic development. This suggests that the city should actively promote the extent of green economic development in the surrounding cities to substantially increase the level of ecological civilization in the area.

② Green production has brought a greater positive impact to the northern cities of the YRD, while it has a smaller impact on the southern cities. The city with a positive coefficient and the largest absolute value of green production level was Wuxi, followed by Changzhou. Meanwhile, the city with a negative coefficient and the largest absolute value was Wenzhou. Green production is closely tied to the impact of the green economy on the degree of ECC. The progress of green production is the foundation for encouraging economic growth and a crucial way of improving the ECC.

③ Green living has a greater positive impact on the central YRD. Meanwhile, it has a smaller impact on the YRD's southern cities. Here, the coefficient is effective and the highest in absolute amount is Chuzhou City, followed by Maanshan City, and where the coefficient is negative and the highest in absolute amount is Taizhou City.

Figure 12 shows that the ECC has improved green progress of eastern coastal cities while restricting the green development of western interior cities in the YRD. Environmental restrictions and urban economic development are the main causes of this divergence [62]. Heavy industry is the primary driver of urban economic building in the western cities of the YRD. This is the main cause of aggravation of the eco-environment and the limitation of UGD. In contrast, the eastern cities have more light industries than heavy industries. This means that there is less environmental interference, ensuring the sustainable green progress of the cities.

① The progress of the economic system has brought positive effects to most cities in the YRD, and only a few cities have negative regression coefficients. Fuyang City has a positive regression coefficient and the highest absolute value, followed by Bozhou City. Meanwhile, Shanghai City has a negative regression coefficient and the highest absolute value. Based on this analysis, economic growth is the primary driver of the green progress of cities like Fuyang and Bozhou and has a stronger impact on it. Economic progress is an important driving force of UGD [31]. Therefore, focusing on improving the local economic construction is a necessary means to enhance UGD. Meanwhile, in cities such as Shanghai, which is different, economic development has a smaller influence on UGD. These cities have a higher level of green development, which has a smaller influence on the nearby cities. Given that the green development level of such cities is greater and influences the other cities, it is advisable for Shanghai or other high-development cities to serve as the region's economic hub to drive the green development level of all the nearby cities.

② While restricting the green progress of the cities in the northwestern part of the YRD, the social system development has increased the level of UGD in the central–eastern part of the YRD. Here, the regression coefficient is positive and has the largest absolute value in Huzhou City, followed by Wuxi City, and is negative and has the largest absolute value in Fuyang City. The primary factor is that urban growth is more advanced and social system progress is at a relatively high level in the central–eastern region of the YRD. This has formed a high-level agglomeration of social system development, which has a higher impact on the UGD of the region. Meanwhile, in the northwest, there has been less urban construction and the level of social development is relatively low. This has formed a low-level agglomeration of urban clusters, which has a smaller impact on the UGD of the region. Therefore, the high-level area should drive the low-level area to develop gradually to the northwest, forming a high level of regional development, to raise the YRD's overall UGD standard.

③ Most cities in the YRD are positively influenced by the development of cultural systems. Only a few cities at the edges have been negatively influenced, among which the largest positive influence coefficient is Yancheng City, followed by Lianyungang City. Meanwhile, the largest negative influence coefficient in absolute value is Fuyang City. Most of the cities with negative influence coefficients are located at the edges of the YRD. One is in the southeast coastal area, and the other is in the northwest inland area. There are differences in geographic and economic factors in the development of these two regions. The economic advance of the southeast coastland has been more rapid and the level of UGD is higher. Meanwhile, the cultural construction has had less influence on the UGD of the region. The economic advance of the northwest inland region is slower, and the extent of social development is lower, leading to the cultural construction of the region being less strong with less influence on the UGD. Therefore, while strongly developing the economic level of the region, the social and cultural construction is also essential, and these have an essential promotional role the UGD of the region.

④ The number of positive impacts from environmental systems on cities in the YRD is 90.24%. Only 9.76% of cities were negative, among which Anqing, Wuhu, and Quzhou had the largest positive impact coefficients. Meanwhile, Wenzhou, Shanghai, and Nantong had negative impacts and the largest absolute values. The influence of the environment on the level of UGD in the YRD is divided into two situations. The first is that cities in the western part of the YRD, such as Anqing City and Wuhu City, have a high level of effect of the environment on the degree of UGD. However, their level of green development is low, indicating that to improve their level of green development, the level of local ecological environment construction should be improved. Cities including Wenzhou City and Shanghai City have a high degree of influence from environmental development on the influence of UGD level, which is relatively low. However, the level of green development of these cities is relatively high. This indicates that the environmental construction of the city is more outstanding and the green industry accounts for a larger proportion of the industrialization. These cities should actively drive the environmental construction of the neighboring cities.

5. Discussion

This paper takes the level of UGD and ECC in the YRD region as the research object, and theoretically analyzes the coupling relationship and driving mechanism between the two. UGD is evaluated in three dimensions: green economy, green production, and green life, while the construction of ecological civilization is evaluated in four dimensions: economic–social–cultural–environment, and a comprehensive evaluation system of UGD and ECC indicators is constructed. On this basis, the spatial and temporal evolution rules of the coupling and coordination of UGD and ECC, as well as the spatial and temporal differential evolution characteristics, are studied. Under the general direction of building a community of human destiny and realizing global green development, the research in this paper is crucial to exploring the path of sustainable development.

First of all, there are few studies on the coupling relationship between UGD and ECC, and studies focusing on the spatial and temporal characteristics and interactive coupling theory are scarce. In view of this, this paper analyzes the influencing factors between UGD and ECC from the connotation concept of the two and studies the interactive relationship between them. Through the study, we find that the existing literature mostly adopts a single dimension or a single indicator to measure UGD and ECC, such as green development efficiency [63] and eco-efficiency [64], but green development efficiency and eco-efficiency are only analyzed from the input–output perspective of production, ignoring the development momentum and urban structure. Similarly, there are studies that construct indicator systems to comprehensively evaluate UGD and ecological civilization construction, such as the PSR model [65] and the DPSIR model [66], which are more comprehensive and systematic in evaluating research objects through indicator systems. It is noteworthy that the existing studies are mainly based on the definitions of green development and ecological civilization in national policy documents and evaluation standards, i.e., “resource use—environmental management—environmental quality—ecological protection -Growth quality”, “resource use—environmental protection—annual evaluation results—public satisfaction—ecological and environmental events” [67,68]. In this paper, the evaluation system of urban development level is based on the “green model”, which selects indicators from economic–production–living dimensions, and for the construction of ecological civilization, this paper selects indicators based on “economic-social-cultural-environmental” multi-dimensions. This paper enriches and improves the research on the evaluation of green development level and ECC in cities.

Second, most previous studies have used green development efficiency and eco-efficiency to study the level of UGD and the level of ECC. These approaches treat UGD and ECC as two independent variables, ignoring the interaction mechanism between UGD and ECC [69]. This study uses a coupled coordination model to further investigate the interaction between the two, and from the analysis of the results, many sustainable development efforts have been conducted in recent years in Shanghai, Nanjing, and other cities to raise the level of green development and ecological civilization in cities. Wei [36] has highlighted that to foster sustainable urban development, we need to constantly adhere to the fundamental principle of peaceful coexistence between humans and the natural world.

This is because sustainable urban development is a necessary and intrinsic component of the ECC. With reference to the combination of the 2019 *Zhejiang Provincial Statistical Yearbook* and *Anhui Provincial Statistical Yearbook*, the "usage of energy per 10,000 yuan of GDP" in Zhejiang Province is 0.26 tons of standard coal, which is 38.68% less than that of Anhui Province. The green growth of Zhejiang cities is less reliant on resource use and places less strain on the environment. This has resulted in a higher level of coordination amongst UGD and ECC. To improve environmental quality, the governments of Zhejiang Province and southern Jiangsu Province have made substantial investments in the development of resource-efficient and environmentally friendly companies [54]. However, the economic growth of Anhui Province and the northern region of Jiangsu Province is primarily dependent on the export of resources and the building of infrastructure, which to some extent compromises ecosystem integrity. The transfer of high-contamination and high-discharge industries to the region has exacerbated the environmental contamination in these areas and places stress on the ecological environment. Several initiatives have been developed by the local authorities to address this issue. Anhui Province's "12th Five-Year Plan" proposed the "Notice of the Anhui Provincial People's Government on the Issuance of the "13th Five-Year Plan" for the implementation of energy conservation and emission reduction", the "13th Five-Year Plan" proposed the "Anhui Province The 13th Five-Year Plan for Ecological Protection and Construction" and the "Jiangsu Province Ecological Protection and Construction Plan (2014–2020)" published by Jiangsu Province in 2015. The promotion of effective coordination between UGD and ECC has been strongly supported by each of these strategies.

Third, this paper provides a new perspective for the spatio-temporal analysis of UGD and ECC. Existing studies mainly use ESDA [53], SDA [70], and spatial autocorrelation models [71], ignoring the spatio-temporal heterogeneity of the degree of influence of different factors. This study examined the spatio-temporal non-stationarity of the influencing factors through GTWR. In order to conduct a more in-depth study, this paper considers regional differences in the level of UGD and ecological civilization construction. This paper considers the regional differences in the level of UGD and ECC. Analyzed from the time dimension, the impact of green economy and green life on the construction of ecological civilization in cities in the YRD region during 2010–2019 is positive and has an increasing trend, indicating that the growth of the green economy is essential for advancing the ECC and is a key factor in raising the degree of ecological civilization [72]. According to the 14th Five-Year Plan, to create a society that is prosperous in all respects, we need to create a green economy, encourage the advancement of science and technology, and continue the transformation and modernization of important sectors of the economy. Key links and key industries, all-round adjustment and optimization of transformation, resolutely fight the battle of pollution prevention and control and construction of the battle. The impact of green production on the construction of ecological civilization is in an unstable trend, the reason is that production is a double-edged sword; vigorous development of production will promote the economic development of the city, but there is the possibility of causing excessive pressure on resources and inhibiting the construction of ecological civilization. Therefore, exploring green development is the way to achieve the building of a community of human destiny. The impact of ecological civilization on the green development of cities is also tending to increase positively, illustrating that the 2019 Master Plan of the YRD Eco-Green Integrated Exploitation Demo Area has accelerated UGD's advancement in the YRD and, to a certain extent, the creative and coordinated growth among UGD and ECC. All four subsystems—economic, social, cultural and environmental—have a positive influence on UGD, which is in line with the findings of Jiexi Zhu [46] and Hu [61] and others. From the spatial dimension, the level of green development and the construction of ecological civilization in cities is centered on high-level urban agglomerations, such as Shanghai and Nanjing–Hangzhou, with the closer the city to the high-level urban agglomerations, the higher the level of development, and the further the distance, the slower the level of development. Based on this, regional governments have introduced corresponding measures to promote the level of green development and ecological civilization in cities, such as the "Strengthen the protection of ecological environment in an all-round way and resolutely fighting the tough battle of pollution prevention." published by Anhui Province in 2018. This was undertaken with the intention of reducing environmental pollution from secondary industries that produce high emissions and pollution levels. They also included a proposal to actively promote the growth of green industries, and protection of the environment in cities is rising along with people's economic levels and the desire for high-quality environments. This is advantageous for the enhancement of ecological and environmental quality. Moreover, the use of big data networks has decreased paper use and enhanced environmental quality.

Fourthly, and finally, the outlook and shortcomings of this paper. In the context of global common construction of a human destiny community, UGD and ECC become important driving forces to promote the construction of high-quality cities, study the coupling coordination and spatial difference of UGD and ECC, clarify the direction of urban development, drive the development of neighboring cities by high level cities, and eventually drive the strategic goal of high quality development of national cities by urban clusters. Due to the limitation of data availability, this paper studied the coupled and coordinated relationship and differences between UGD and ECC during the 10 years from 2010–2019, and seldom considered some micro-level factors when constructing the comprehensive evaluation system of ECC and UGD, and how to accurately measure ECC and UGD remains the main research direction in the future.

6. Conclusions and Recommendations

6.1. Conclusions

Promoting green and sustainable development of the city is an important element to resolutely fight the battle of pollution prevention and control, crack urban diseases, improve the city's taste and build a green city, and achieve the scientific development of information technology in the city at a higher level. Existing studies have focused primarily on UGD and ECC's qualitative relationship with the coordination relationship inside a single system, while disregarding UGD and ECC's coordination relationship and inner mechanism. Therefore, the CCDM and GTWR models were combined to examine the coupling and coordination effects and spatio-temporal heterogeneity among UGD and ECC of prefecture-level cities in the YRD from 2010 to 2019.

The results of the study have shown that: ① From 2010 to 2019, the level of UGD gradually increased, and the priority of urban development shifted from actively growing industrial level and driving economic building to insisting on ecological conservation and driving green development. Eastern coastal cities of the YRD have more green development than those in the western interior. The rate of ECC has indicated a slow but steady increase from 2010 to 2019. Meanwhile, the importance of the influence of economic system and cultural system on the ECC is higher among all evaluation indicators. The ECC in coastal cities in the southeastern YRD is better than other cities. ② The level of coordination among UGD and ECC inside the YRD fluctuated upward from 2010 to 2019. It underwent the change from lagging UGD to lagging ECC, evolved from a phase with no correlation to a primary coordinated phase. Meanwhile, the degree of coordination in the eastern coastal cities in the YRD has become higher than that in the western inland cities. ③ The UGD and ECC interaction tends to be significant, according to the GTWR model. The UGD and ECC's adverse effect between YRD is concentrated in the northwestern inland cities, while the positive effect of UGD and ECC is concentrated in the southeastern coastal cities. This has indicated that UGD and ECC complement each other, and UGD is the fundamental driving force of ECC, while ECC is the goal and orientation of UGD.

6.2. Policy Recommendations

To improve the degree of coordination among UGD and ECC and considering the differences in geographic location, resource endowment and urban development patterns, this study has proposed the following recommendations:

The overall level of green development in the country should continue to be improved, and "development" and "green" should be coordinated and advanced. Effective handling of the harmony between humans and nature should always be prioritized in the specific urbanization process economic development. Chinese President Xi Jinping has said everyone should abide by the green development tenets that "green water and green mountains are the silver mountain of gold", and "harmony between humans and nature" is central to it. He said will fully implement the spirit of the 20th Party Congress in urban production, people's lives, and ecological protection. We need to pay full attention to the unbalanced spatial characteristics of green development, and governments at all levels should actively take measures to effectively narrow the gap between the economic development level and industrial structure of each region.

The focus should be on improving the level of green production in the city to achieve the purpose of substantially improving the level of green development. In the Opinions on Promoting Green Development in Urban and Rural Construction issued by the State Council, it is stated that urban planning and design should adhere to resource recycling, green sustainable development, regeneration, and continuous recycling, implement green transformation of traditional industries, develop green industries, and build a sound green industrial system. In its socio-economic development, China insists on implementing the new basic principles of circular economy, i.e., reduction, resourceization, resource repositioning, resource replacement and harmless storage, realizing intensive recycling of resources, reducing the solid waste that may be generated, promoting the coordinated development of green regions, and developing new green industries and models to contribute significantly to the realization of building a community of human destiny.

The areas with higher levels of green development should be used as the center to radiate the surrounding areas and drive the development of the surrounding areas. Regions with lower levels of green development can then learn from the development model of regions with higher levels. Meanwhile, inter-regional cooperation should be guided to benefit from complementary advantages and narrow the differences between regions. Depending on the environment and resource bearing capacity, the density of current development, and the potential for future development, each region should gradually form the main function positioning division of labor to form a benign interaction between cities and coordinate development.

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Vulnerability Assessment of Ecological–Economic–Social Systems in Urban Agglomerations in Arid Regions—A Case Study of Urumqi–Changji–Shihezi Urban Agglomeration

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Abstract: This study aims to clarify the vulnerability characteristics of the ecological–economic–social system of oasis city clusters in arid zones, promote the deepening of research on the sustainable development of urban clusters, and provide crucial practical reference significance for solving the series of problems brought about by urbanization. This article takes the arid zone oasis city cluster, the Urumqi–Changji–Shihezi urban agglomeration, as the research object and constructs an indicator system from three dimensions of ecological environment, regional economic, and social development, and adopts the comprehensive index method, GeoDetector, the GM(1, 1) gray prediction model, and other methods to study the vulnerability pattern and spatial and temporal changes of the urban cluster from 2009 to 2018. The results show that (1) from 2009 to 2018, the change in the integrated ecological–economic–social system vulnerability index of the Urumqi–Changji–Shihezi urban agglomeration shows a general downward trend, followed by significant differences in the vulnerability of each dimension, with an average vulnerability index of 1.8846, 1.6377, and 0.9831 for the social vulnerability, regional economic, and ecological environment dimensions, respectively; (2) the evolution of the spatial pattern of changes in the vulnerability index of different systems in each region of the Urumqi–Changji–Shihezi urban agglomeration tends to change from large to slight spatial differences, in which the social and ecological environmental vulnerability changes are more prominent in addition to the vulnerability changes of the regional economy; (3) parkland area per capita, arable land area per capita, GDP per capita, social fixed asset investment, population density, and urban road area per capita are the main drivers of decreasing vulnerability of ecological–economic–social systems in urban agglomerations; (4) by predicting and calculating the vulnerability index of each region of the ecological–economic–social system of urban agglomerations, it is found that the vulnerability index of urban agglomerations will show a decreasing trend from 2009 to 2018, and the difference of the vulnerability index between systems will narrow; (5) finally, targeted countermeasures and suggestions to reduce the vulnerability of ecological–economic–social systems are proposed to provide scientific references for the sustainable development of arid oasis cities.

Keywords: vulnerability assessment; oasis urban agglomerations in arid zones; trend prediction; evaluation indicator system; Urumqi–Changji–Shihezi urban agglomeration

1. Introduction

The concept of vulnerability was first proposed by the scholar Timmernan P [1] in geography. With continuous research, vulnerability study gradually extended from natural disasters to other fields such as geography, ecology, economics, etc. Vulnerability-based research is maturing and has become one of the focal points of many international scientific institutions. The International Human Dimensions Program on Global Environmental

Change (IHDP) considers vulnerability one of its four core issues [2]. The definition of vulnerability varies depending on the object of study and disciplinary perspective, with the United Nations Intergovernmental Panel on Climate Change (IPCC) defining vulnerability in its Third Assessment Report as the degree of likelihood that a system, its subsystems, and system components are likely to cause damage under external stress [3]. Chuanglin Fang and other scholars [4] proposed that urban vulnerability refers to the coping ability of cities to resist disturbances from internal and external natural and human factors such as resources, ecological environment, and economic and social development in the development process. The city becomes vulnerable when this coping capacity against disturbances falls below a certain critical threshold. Vulnerability assessment, on the other hand, refers to the degree or likelihood of damage to a regional system adversely affected by certain anthropogenic activities through scientific methods [5].

Urban vulnerability assessment is increasingly becoming an essential issue on the policy agenda and in academia [6]. Research on urban vulnerability has grown considerably in the past few years but remains primarily limited by interdisciplinary differences in definition and scope [7]. The earliest studies of urban vulnerability focused on natural hazards and climate change, such as the vulnerability to natural hazards of specific cities or areas such as flood plains, coastal areas and seismic zones in specific external contexts; for example, C handra and Gaganis' study of the Nadi River Basin in the Fiji Islands found that the vulnerability to flooding in the basin was increasing [8]; Herslund et al. found a substantial increase in urban vulnerability due to climate change-induced risks in sub-Saharan African cities, and that continuing business-as-usual urban development patterns will reduce the resilience and adaptive capacity of cities to cope with the combined impacts of urbanization and climate change [9]; Tapia et al. introduced an indicator-based vulnerability assessment through five climate threats in 571 European cities which will facilitate the understanding of urban climate change risks and the development of effective adaptation policies [10]; and we note Kermanshah et al., Rasch, and Zhang et al., whose assessment of urban vulnerability to climate threats will help strengthen the adaptive capacity of cities in the face of climate change and natural disasters [11–13]. Urban vulnerability studies also focus on the vulnerability assessment of a city subsystem or the vulnerability of human–land coupled systems. The subsystems include the economic, ecological, environmental, and social systems. For example, some scholars, Rocha and Moreira, focus on the new market economy countries [14], and Ren Chongqiang and others use the Chinese provinces as the main study area and conduct a vulnerability analysis of the economic system in the study area [15]. In addition, Pan et al. conducted an ecosystem vulnerability analysis based on a habitat–structure–function framework in the Yangtze River basin in China [16]. In a study by Duy et al. in Vietnam, it was found that resilient transportation systems can reduce the vulnerability of cities to flooding [17], and Sterzel et al. assessed essential factors contributing to the significant differences in vulnerability through a study of rapid urbanization in coastal areas [18]. As times progress, there is a growing awareness of the cumulative impact of environmental, political, social, and economic risks on the ability of cities to function in times of shock and stress and a greater need to apply integrated research to understand the vulnerability of these rapidly growing cities to chronic and acute stresses and shocks [19]; for example, He et al. conducted a study on tourism-economy-ecosystem vulnerability in the Yangtze River Economic Zone to analyze the spatial and temporal evolution of its vulnerability and calculate the future vulnerability index prediction [20]; Chen et al. took Henan Province as an example to construct an evaluation model for vulnerability analysis from the coupled perspective of resource, ecological environment, economic and social vulnerability, and the results of the study showed that the overall vulnerability of Henan Province was decreasing between 2007 and 2016 [21]; moreover, scholar WU, R used Longnan city as the study area to measure the vulnerability of the coupled economic-social–ecological system of its districts and counties and concluded that the city should reduce vulnerability by enhancing the economic radiation capacity and improving the level of public services [22].

Urban vulnerability is also studied for specific types of cities. For example, assessing the vulnerability of resource-based cities is conducive to sustainable development [23–25]. Several scholars conducted a comprehensive and scientific analysis of the vulnerability characteristics of three Chinese cities with more than 10 million tons of coal mining. They identified the leading causes of natural and social vulnerability; the study is conducive to solving historical problems such as soil erosion and transforming the industrial structure to achieve sustainable urban economic development [26].

In natural disasters, climate change, economic, ecological, environmental, and social systems, and specific types of cities, many research results have been achieved in vulnerability assessment, and its technical methods have been initially developed. Some evaluation methods, such as the composite index method [27] and principal component analysis [28,29], have been widely used. The main components of current vulnerability assessment are quantitative evaluation models, such as the DRASTIC model [30], DPSIR model [31,32], FAHP model [33], etc., followed by the construction of indicator systems, such as the coastal vulnerability and social vulnerability indicator system [34], the ecosystem vulnerability assessment framework [35], the vulnerability framework of the coupled human-environment system [36], and the rural livelihood analysis framework [37]. There are other innovative technical approaches to vulnerability assessment; Hagenlocher, M et al. proposed an innovative approach based on a modular indicator library for assessing multi-hazard risks in global coastal deltas and internal social systems [38]; de Chazal, J. et al. proposed a methodology for assessing the vulnerability of social–ecological systems with direct correlation to multi-stakeholder values [39]. Metzger, M.J. et al. proposed a new ecosystem assessment methodology for ATEAM land use scenarios [40]; Teck, S. et al. evaluated marine ecosystem vulnerability using an expert evaluation method [41]; Thirumalaivasan, D. et al. developed an AHP-DRASTIC software package for specific aquifer vulnerability assessment studies [42]. Recently, GIS and remote sensing technologies have been combined with vulnerability assessment methods [43–47]. The vulnerability maps generated help reveal the spatial patterns of vulnerability and identify vulnerability hotspot areas.

The comprehensive study found that urban vulnerability studies are fragmented and relatively independent, leading to a lack of comparability between research data and making it challenging to assess by comparing data from independent studies [4]. Current urban vulnerability research is dominated by cities with high levels of economic development in the region. However, there is a paucity of research on cities with low levels of economic development in inland arid zones. Vulnerability studies in arid zones have mainly focused on single-system vulnerabilities such as economic systems [48,49] and ecosystems [50,51], while there are fewer studies on urban hybrid system vulnerability [52,53].

Under the background of an arid climate and natural environment, the ecological environment of urban clusters in the oasis zone is exceptionally fragile, and the rapid development of urban clusters and economic growth is exacerbating the pressure on the ecological environment; at the same time, under the unique urban development environment of the arid zone, the size of the oasis and the spatial distance between them restrict the economic activities of oasis cities to a certain extent. The oasis urban economy shows prominent vulnerability characteristics. Secondly, the fragile ecological environment and regional economy will inevitably pressure the social system. The fragility of the ecological environment, regional economy, and social system restrict urban clusters' upgrading and high-quality development. Studies based on the vulnerability of oasis cities in arid zones with low economic development levels are scarce, and the Urumqi–Changji–Shihezi urban agglomeration, as a new opportunity for the development of Xinjiang, is of strategic importance for the economic and social development of the whole Xinjiang and northwest regions.

Based on the above analysis, the main objectives of this paper are as follows: (1) to construct a research framework and a comprehensive evaluation system for the vulnerability of the ecological–economic–social system of the urban agglomeration; (2) to measure the vulnerability of the ecological–economic–social tri-system of the Urumqi–Changji–Shihezi urban agglomeration from 2009 to 2018 and analyze its spatial and temporal evolution through the comprehensive index method; (3) to use the geographic detector to study the factors influencing the decline of the vulnerability index of the Urumqi–Changji–Shihezi urban agglomeration; (4) furthermore, use the gray prediction model to predict the vulnerability of the three systems of Urumqi–Changji–Shihezi urban agglomeration in the next seven years; (5) finally, to propose development measures for Urumqi–Changji–Shihezi urban agglomeration in response to the evaluation results to provide theoretical support for the sustainable development of the oasis urban agglomeration in the arid zone.

2. Materials and Methods

2.1. Study Area

The Urumqi–Changji–Shihezi urban agglomeration (Figure 1 below) is one of the 19 critical urban clusters planned for urban cluster construction at the national level and one of the eight typical representative urban clusters identified in the Urban System Planning of Xinjiang Uygur Autonomous Region (2012–2030). The total area of the Urumqi–Changji–Shihezi urban agglomeration is 63,800 km^2, with Urumqi as the "heart and brain", its scope also includes Shihezi, Changji, Fukang, Wujiaqu, Shawan, and Hutubi County, Manas County, and other six cities and two counties, as well as the sixth division, the eighth division, and the twelfth division of the Corps.

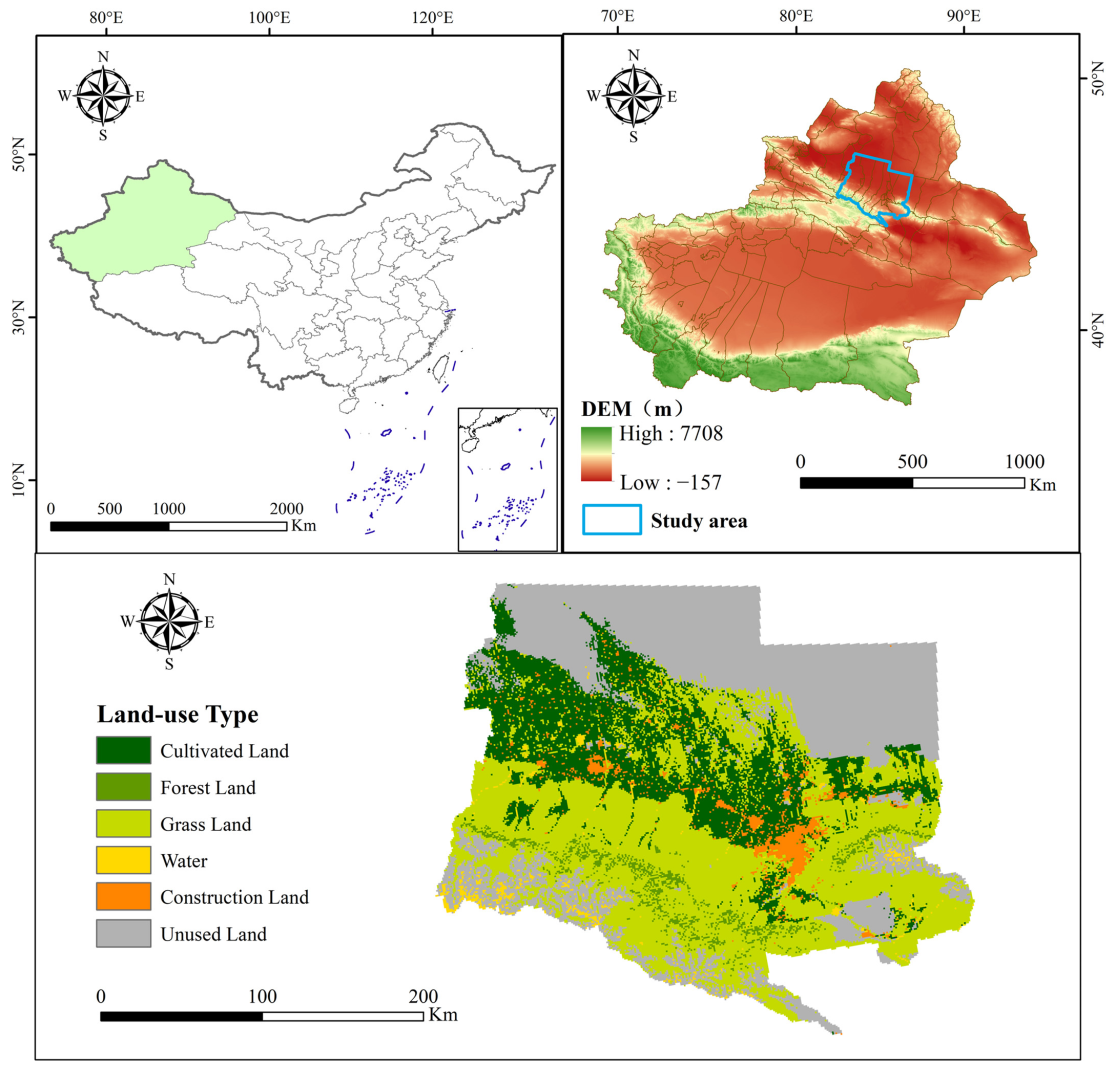

Figure 1. Overview of the Urumqi–Changji–Shihezi urban agglomeration.

Its natural conditions are superior; it is located on the southern edge of the Junggar Basin, with a moderate temperate climate and an annual average temperature of 5–7.5 °C; at the same time, the water and mineral resources are rich and there is an excellent economic base and convenient transportation; so, the carrying capacity of resources and environment is strong. The population and towns are also more concentrated; according to the data of the seventh census in 2020, the population is about 8.673 million people, accounting for more than 33.5% of the proportion of Xinjiang. With a gross regional product of 499.769 billion yuan, the Urumqi–Changji–Shihezi urban agglomeration is the future center and lifeline of economic and social development in Xinjiang. Due to the incomplete data for various urban development and national economic statistics of Wujiaqu City, Wujiaqu City was excluded as the study area in this paper for the vulnerability study of Urumqi–Changji–Shihezi urban agglomeration to ensure the scientificity and credibility of the evaluation results.

2.2. Data Sources

The data on various urban development and national economic statistical indicators involved in the study were mainly collected and compiled from the Xinjiang Statistical Yearbook, Urumqi Statistical Yearbook, Urumqi Yearbook, and the national economic and social development bulletins of counties and cities from 2010 to 2019. Some missing data were supplemented and perfected by interpolation.

2.3. Research Indicator System

This paper synthesizes the research on the three ecological–environment–regional economic–social development systems, follows the principles of completeness, uniqueness, objectivity, feasibility, and systematization, and has constructed a vulnerability evaluation index architecture ecological–economic–social system for the Urumqi–Changji–Shihezi agglomeration (Table 1 below). There are 23 evaluation indicators, which are divided into positive indicators and reverse indicators. The negative indicators are inversely proportional to the vulnerability of the system. The larger the value, the smaller the vulnerability; the positive indicators are positively proportional to the system's vulnerability. The larger the value, the greater the system's vulnerability.

Table 1. Ecological–economic–social vulnerability evaluation index system of Urumqi–Changji–Shihezi urban agglomeration.

Target Layer	Criterion Layer	Index Layer	Indicator Description	Index Properties	Weight
Ecosystem Vulnerability	Ecological Vulnerability	Park green space per capita (m^2-people)	Living environment and quality of life for urban residents	–	0.017025
		Greening coverage of built-up areas (%)	Reflects the urban ecological environment	–	0.0085627
		Cultivated land per capita (hectares)	Pressure on the ecosystem	+	0.0091961
	Environmental Vulnerability	Wastewater treatment rate (%)	Environmental Governance Capacity	–	0.0086132
		Domestic waste removal volume (million tons)	Domestic waste treatment capacity	–	0.0963664
		Total number of special vehicles for amenities and sanitation (units)	Environmental cleanliness protection capacity	–	0.1175512
Regional economic vulnerability	Economic structural vulnerability	The proportion of primary industry (%)	Reflect the level of regional modernization	+	0.0188583
		Urbanization rate (%)	Reflects the urbanization process	–	0.022392
		Share of industrial value added in GDP (%)	The pull of industry on the economy	–	0.018683

Table 1. *Cont.*

Target Layer	Criterion Layer	Index Layer	Indicator Description	Index Properties	Weight
	Economic efficiency vulnerability	Local revenue (billion yuan)	Reflects the degree of economic development	−	0.1021245
		GDP per capita (RMB)	Economic level of regional residents per capita	−	0.0142876
		Total retail sales of social consumer goods (million yuan)	Reflects the economic prosperity	−	0.1009445
		Total social fixed asset investment (million yuan)	Reflects economic structure and quality	−	0.0637112
Social system vulnerability	Human Development Vulnerability	Population density (persons/km^2)	Social Development Demographic Pressure Indicators	+	0.0096287
		The average wage of employed workers (yuan)	Reflects regional wage levels	−	0.0123461
	Infrastructure Vulnerability	Urban road area per capita (m^2)	Convenience of urban transportation	−	0.0229304
		Drainage pipeline density (km/km^2)	Reflects the city's sewage diversion capacity	−	0.0236853
		Gas penetration rate (%)	Utility modernization level	−	0.0070537
		Number of public toilets (one)	Sewage facilities construction capacity	−	0.0965437
	Social Environmental Vulnerability	Disposable income per urban resident (yuan)	Reflects the livelihood capacity and real standard of living of the society's residents	−	0.0219353
		Net income per capita of rural residents (yuan)		−	0.0159044
		Number of beds in medical and health institutions (sheets)	City Public Service Levels	−	0.0959529
		Number of urban basic pension insurance participants (persons)	Social Security Capability	−	0.0957034

3. Research Methods

3.1. The Entropy Method

This paper uses the Entropy method to determine the weights of each evaluation index. The main steps are as follows.

(1) Standardization of the original data

According to the ecological–economic–social system evaluation system obtained in the previous section, to eliminate the influence of the different data outlines and size disparity on the different calculation results, the extreme difference standardization method is introduced to standardize the raw data.

For positive indicators, there are:

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \tag{1}$$

For negative indicators, there are:

$$y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \tag{2}$$

where y_{ij} is the standardized data value; x_{ij} is the original data value, where $i(i = 1,2,3,\ldots,m)$ is the number of sequences in the evaluation area; $j(j = 1,2,3,\ldots,n)$ is the number of evaluation index points; $\max(x_{ij})$ and $\min(x_{ij})$ are the maximum and minimum values of the jth index of the original data area i, respectively.

(2) Calculate the proportion of the jth indicator of region i to this indicator

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{3}$$

(3) Calculate the entropy value E and information utility value D of the jth indicator of region i

$$E_j = -(In\ m)^{-1}\sum_{i=1}^{m} P_{ij}, (j = 1, 2, ..., m); \tag{4}$$

$$D_j = 1 - E_j, (1 \ll j \ll n). \tag{5}$$

(4) Define the weight of the jth indicator

$$W_j = \frac{D_j}{\sum_{j=1}^{n} D_j} \tag{6}$$

where W_j is the weight of the jth indicator of the ith evaluation object.

3.2. Vulnerability Evaluation Method

Vulnerability assessment is an essential element of current vulnerability research. In this paper, the composite index method, which is more commonly used to determine urban vulnerability, is used to evaluate the vulnerability of the ecological–economic–social system of the Urumqi–Changji–Shihezi urban agglomeration. The integrated index method establishes a system of evaluation indicators from the performance characteristics and causes of vulnerability. It uses statistical methods or other mathematical methods to synthesize them into a vulnerability index to express the relative magnitude of the vulnerability of the evaluation unit [5]. The vulnerability index is calculated by the following formula.

The vulnerability index for the second tier of indicators is calculated with the following formula.

Ecological system:

$$UVI_{\mathrm{e}} = \sum_{i=1}^{m} y_{ij} \bullet W_{ij} \tag{7}$$

Regional Economic System:

$$UVI_{\mathrm{f}} = \sum_{i=1}^{m} y_{ij} \bullet W_{ij} \tag{8}$$

Social System:

$$UVI_s = \sum_{i=1}^{m} y_{ij} \bullet W_{ij} \tag{9}$$

Ecological–economic–social complex systems:

$$UVI = UVI_e + UVI_f + UVI_s \tag{10}$$

where W is the weight of each index, UVI_e, UVI_f, UVI_s indicates the vulnerability index of each system of ecological environment, regional economy, and social development, respectively. The vulnerability of the ecological–economic–social complex system consists of the ecological and environmental system vulnerability UVI_e, the regional economic system vulnerability UVI_f, and the social development system vulnerability UVI_s added together.

3.3. Vulnerability Classification Method

This paper classifies the vulnerability index of the Urumqi–Changji–Shihezi urban agglomeration based on the natural interruption point grading method in ArcGIS, with five vulnerability levels from low to high: Slight, Light, Medium, Heavy, Extreme, respectively (Table 2 below).

Table 2. Eco–environmental–regional economic–social system vulnerability level.

Vulnerability Level	Slight	Light	Medium	Heavy	Extreme
Integrated system	≤0.6301	0.6302~0.6670	0.6671~0.7647	0.7648~0.7756	0.7757~0.8387
Ecological system	≤0.1202	0.1203~0.1302	0.1303~0.1581	0.1582~0.1754	0.1755~0.2293
Regional economic system	≤0.2031	0.2032~0.2148	0.2149~0.2419	0.2420~0.2695	0.2696~0.3132
Social system	0.2941~0.2962	0.2963~0.3068	0.3069~0.3214	0.3215~0.3472	0.3473~0.3583

3.4. Geodetector

This paper uses GeoDetector to detect the main influencing factors of ecological–economic–social system vulnerability in the Urumqi–Changji–Shihezi urban agglomeration. GeoDetector is a set of statistical methods that are used to detect spatial differentiation and reveal the driving forces behind it [54], with the expression:

$$q = 1 - \frac{\sum_{h-1}^{L} N_h \sigma^2 h}{N\sigma^2} \tag{11}$$

where L is the stratification of ecological–economic–social system vulnerability Y or indicator factor X in the Urumqi–Changji–Shihezi urban agglomeration, N_h and $\sigma^2 h$ are the number of cells and variance of layer H, respectively; N and σ^2 represent the number of cells and variance of the study area, respectively. q is the degree of influence of the indicator factor on the change in vulnerability, and a higher value of q indicates a stronger explanatory power of the indicator factor on vulnerability.

The factors x were classified into five categories by the natural interruption point hierarchy of ArcGIS, discretized, and the independent numerical variables were transformed into type quantities. Then the samples (Y, X) were read into the GeoDetector software to run the analysis, where the dependent variable Y was the vulnerability index. This paper investigates the degree of influence of each indicator factor of the ecological environment, regional economic, and social development systems on the integrated vulnerability of the urban agglomeration, respectively, during the decade. It focuses on the influence of each system's top two detection factors on the integrated vulnerability of the ecological–economic–social system of the Urumqi–Changji–Shihezi urban agglomeration.

3.5. GM(1, 1) Gray Prediction Model

In this paper, we use the gray prediction model to quantitatively predict the changes in vulnerability of the Urumqi–Changji–Shihezi urban agglomeration with the following steps and formulae [55]:

A. Let the time series $X_0 = \{x_0(1), x_0(2), \ldots\ldots, x_0(n)\}$ have n observations and generate a new series $X_1 = \{x_1(1), x_1(2), \ldots\ldots, x_1(n)\}$ by accumulating the original series, then the corresponding differential equation of the GM(1, 1) model is

$$\frac{dX_1}{dt} + aX_1 = \mu \tag{12}$$

where a is the developmental ash number; μ is the endogenous control ash number;

B. Let $\hat{a}$ be the parameter vector to be estimated; which can be solved by using the least squares method to obtain and solve the differential equation to obtain the prediction model.

$$x_1{}^T \hat{X}_1(k+1) = [x_0(1) - \frac{\mu}{a}]e^{-ak} + \frac{\mu}{a}; \tag{13}$$

$$(k = 1, 2, ..., n)$$

C. The accuracy test of the gray prediction formula is generally given in the following Table 3. If both P and C are within the allowed range, the predicted value of the indicator can be calculated. Otherwise, the formula needs to be re-corrected by analyzing the residual series.

Table 3. The accurary test grade of gray forecast model.

Accuracy Class	P	C	Accuracy Class	P	C
High	>0.95	<0.35	Basic qualified	>0.70	<0.65
Qualified	>0.80	<0.50	Unqualified	≤0.70	≥0.65

4. Results

4.1. Temporal Evolution Characteristics of the Combined Vulnerability of Urban Agglomerations

In this paper, based on the established ecological–economic–social system vulnerability index system of the Urumqi–Changji–Shihezi urban agglomeration, the weights of the evaluation indexes are determined using the entropy value method. The vulnerability indices of the composite and separate ecological–economic–social systems are calculated by the integrated index method. The calculated vulnerability indices are expressed visually using Origin 2021, as shown in Figure 2 below. Observing the changing trend of the vulnerability index of ecological–economic–social systems in the Urumqi–Changji–Shihezi urban agglomeration from a perspective of totality, it can be found that the overall change trend of the integrated vulnerability of the Urumqi–Changji–Shihezi urban agglomeration from 2009 to 2018 is slowly decreasing, and the vulnerability index of each system is decreasing in fluctuation. The composite vulnerability index decreases over the ten years, from 5.2653 to 3.9759. The composite vulnerability index decreases faster and then slower, using 2014 as the time point.

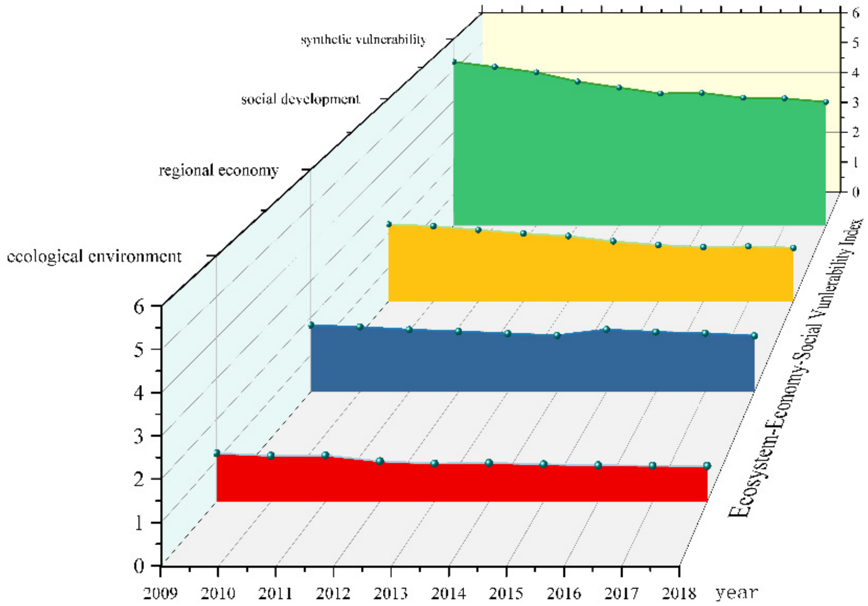

Figure 2. Trend of vulnerability index of ecological–economic–social system in Urumqi–Changji–Shihezi urban agglomeration.

4.2. Time Course of Subdimensional Vulnerability Evolution

The vulnerability of each dimension of the Urumqi–Changji–Shihezi urban agglomeration varies widely, with the highest social vulnerability, the second highest regional economic vulnerability, and the lowest ecological and environmental vulnerability, whose average vulnerability indices are 1.8846, 1.6377, and 0.9831, respectively. During the study period, the vulnerability of the social development system decreased significantly, the regional economic vulnerability showed a changing trend of decreasing, then increasing, and then decreasing, and the change of the vulnerability of the ecological environment system was more stable and showed a slow decreasing trend.

4.3. Spatial Differentiation Characteristics of Vulnerability of Subdimensional Urban Clusters

The vulnerability values of each region of the Urumqi–Changji–Shihezi urban agglomeration from 2009 to 2018 were spatially visualized using Arcgis 10.6 software and divided into three-time nodes—2009, 2013, and 2018—to obtain the spatial distribution of vulnerability levels in each region of the Urumqi–Changji–Shihezi urban agglomeration, as shown in Figure 3 below. From the figure, it can be found that the spatial pattern evolution trend of the vulnerability index changes of different systems in each region of the Urumqi–Changji–Shihezi urban agglomeration is as follows: overall, the difference of the spatial evolution pattern of the vulnerability index of ecological–economic–social systems in the Urumqi–Changji–Shihezi urban agglomeration changes from large to small, among which the change of regional economic vulnerability is smaller, and the change of social and ecological environmental vulnerability is larger.

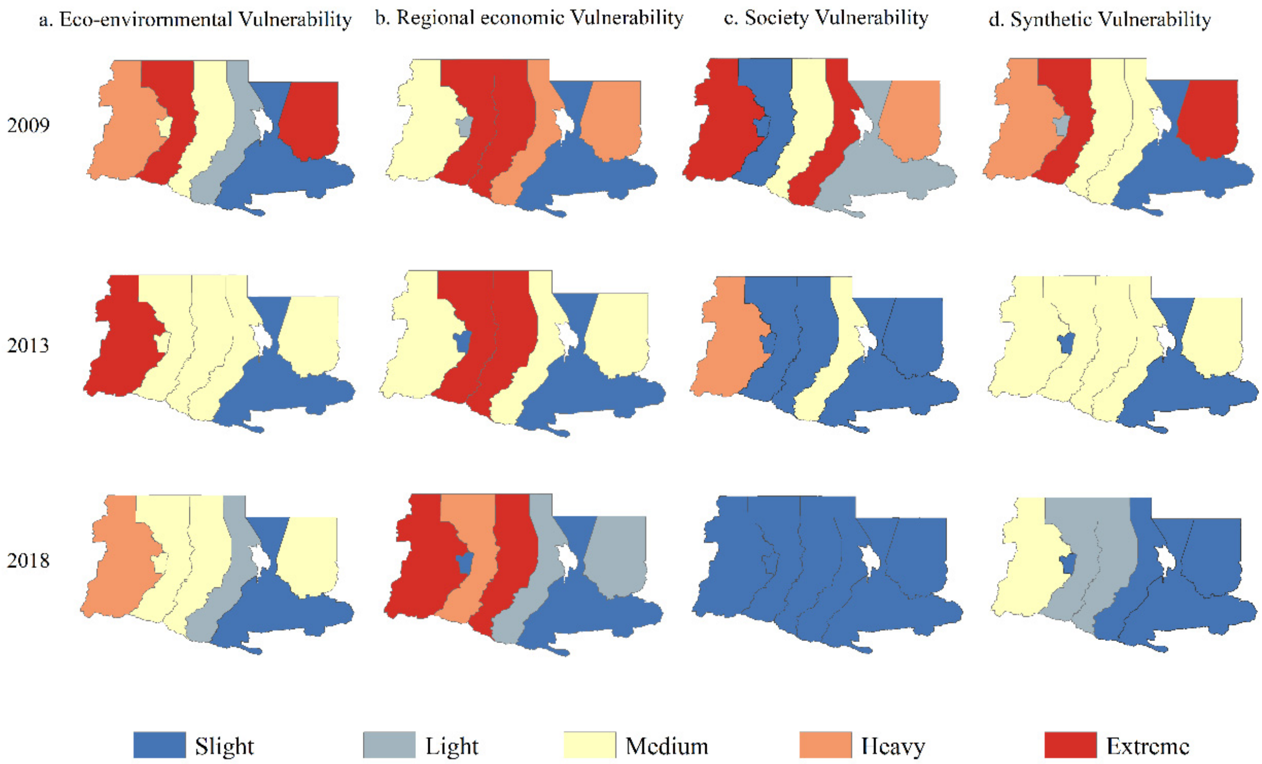

Figure 3. Spatial differentiation of sub-dimensions and integrated vulnerability of the Urumqi–Changji–Shihezi urban agglomeration.

Among the comprehensive vulnerability, the spatial pattern evolutionary representation of the vulnerability index in Urumqi is more stable and has been maintained at low vulnerability; the vulnerability level of the remaining areas, including Shawan, Shihezi, Changji, Fukang, Manas, and Hutubi counties, have all decreased, with Fukang having the most significant decrease.

The overall ecological vulnerability rank is higher in eastern cities and lower in western cities; the regional economic vulnerability rank has a considerable spatial variation. Among them, the spatial evolution pattern of vulnerability index levels in Urumqi, Hutubi County, and Shihezi City is very stable. It has been maintained at low, medium vulnerability, and medium, respectively. In contrast, the vulnerability levels in Manas County and Fukang City change significantly from high to medium vulnerability, while the vulnerability levels in Shawan City and Changji City rise and fall.

The spatial pattern of vulnerability levels in the regional economic dimension varies widely, with Manas County and Hutubi County in the central part of the region having high vulnerability levels in 2009, both of which have been high from 2009 to 2018, and the vulnerability level of Shawan City has also increased from medium to high vulnerability. While Urumqi city has maintained a low vulnerability, the vulnerability levels of other regions, including Shihezi city, Manas county, Changji city, and Fukang city, have all decreased to different degrees.

The vulnerability level of the social dimension declined most significantly, with all of them gradually decreasing to low vulnerability from 2009 to 2018. Shawan and Changji cities were the most significant, gradually decreasing from high vulnerability to low vulnerability, while the vulnerability level of Shihezi city and Manas county was the most stable, remaining at low vulnerability. This is followed by Fukang city, Hutubi county, and Urumqi city, where the vulnerability levels have all decreased to different degrees.

4.4. Forecast of Ecological–Economic–Social System Vulnerability Development in the Urumqi–Changji–Shihezi Urban Agglomeration

As seen from Table 4, the vulnerability index of ecological–economic–social systems in the Urumqi–Changji–Shihezi urban agglomeration shows a decreasing trend, and the difference in vulnerability index between systems is reduced. Urumqi city has the lowest vulnerability index of 0.0721 in 2025, followed by Shihezi city, Changji city, Manas county, Fukang city, Hutubi county, and Shawan city, among which Shawan city is predicted to have the highest vulnerability index.

Table 4. Projected development of ecological–economic–social system vulnerability in the Urumqi–Changji–Shihezi urban agglomeration.

Region	2019	2020	2021	2022	2023	2024	2025	2019–2025
Urumqi City	0.2463	0.2154	0.1853	0.1559	0.1273	0.0993	0.0721	1.1016
Shihezi City	0.4853	0.4705	0.4562	0.4423	0.4288	0.4157	0.4030	3.1018
Changji City	0.5723	0.5565	0.5412	0.5263	0.5118	0.4977	0.4840	3.6898
Fukang City	0.5760	0.5607	0.5459	0.5314	0.5173	0.5036	0.4903	3.7252
Hutubi County	0.5911	0.5760	0.5614	0.5471	0.5331	0.5195	0.5063	3.8344
Manas County	0.5871	0.5660	0.5457	0.5261	0.5072	0.4889	0.4713	3.6923
Shawan City	0.6995	0.6929	0.6864	0.6799	0.6736	0.6672	0.6609	4.7605

5. Discussion

5.1. Dominant Factors Affecting the Vulnerability of Different Systems

5.1.1. Dominant Factors Affecting the Reduction of Ecosystem Vulnerability

As shown in Table 5, the average magnitude of the influence of the detection factors in the ecosystem on the changes in the vulnerability of the ecological–economic–social system in the Urumqi–Changji–Shihezi urban agglomeration is, in order, park green area per capita (X1) > arable land area per capita (X6) > the total number of vehicles dedicated to amenities and sanitation (X5) > green coverage of built-up areas (X2) > sewage treatment rate (X3) > domestic waste removal volume (X4). As an essential part of urban vegetation cover, urban green space systems can maintain urban ecosystem services and improve the human living environment [51], and insufficient vegetation cover is the main environmental factor [56] leading to land degradation. This is consistent with the findings of Penghua et al. and Zhang et al. [57,58]. The impact of arable land area per capita on ecosystem vulnerability in urban agglomerations is second only to parkland area per capita. Arable land is the type of land use on which humans depend and is an essential condition for ecosystem development. Therefore, the increase or decrease of arable land per capita impacts ecosystem vulnerability, consistent with Pan et al.'s findings [16]. The urban expansion causes land use change and thus decreases ecological vulnerability, especially in areas with significant land use change where agriculture and animal husbandry intermingle [59]. The oasis is mainly located in the north of Xinjiang. The economic development situation was good at the beginning of western development. The population is gradually dense, and the demand for agricultural land increases, so the per capita arable land area of the Urumqi–Changji–Shihezi urban agglomeration is rising. However, due to reasonable development and utilization, there is no negative impact on the ecological environment, so the ecological environment vulnerability is reduced.

Table 5. Results of the GeoDetector of ecological–economic–social system vulnerability in the Urumqi–Changji–Shihezi urban agglomeration.

Detection Factor	Detection Results by Years									
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
X1	0.5943	0.8224	0.9488	0.8983	0.5713	0.8247	0.5997	0.6088	0.5482	0.5258
X2	0.9080	0.9935	0.6632	0.4131	0.9974	0.3921	0.9058	0.6088	0.7807	0.9560
X3	0.8388	0.9856	0.4889	0.9810	0.9953	0.9826	0.9479	0.9504	0.9305	0.3139
X4	0.8483	0.9569	0.9728	0.9940	0.8553	0.9855	0.9013	0.9861	0.8419	0.8782
X5	0.8874	0.8912	0.8872	0.9776	0.9801	0.9803	0.8575	0.9498	0.9412	0.9561
X6	0.8700	0.9917	0.9519	0.9874	0.9883	0.9921	0.9565	0.9623	0.7802	0.7093
X7	0.8700	0.9512	0.8886	0.9933	0.9987	0.8652	0.8323	0.8316	0.5250	0.4753
X8	0.7780	0.8564	0.9107	0.8115	0.7107	0.7682	0.5164	0.5491	0.1648	0.4830
X9	0.7254	0.8836	0.6210	0.9556	0.4482	0.9165	0.5643	0.5615	0.4149	0.9456
X10	0.8144	0.8134	0.8872	0.9776	0.9816	0.9803	0.9437	0.9031	0.9579	0.9781
X11	0.3709	0.9443	0.8259	0.9110	0.3792	0.3622	0.4532	0.4356	0.7808	0.7061
X12	0.8884	0.7503	0.8799	0.9530	0.8506	0.9060	0.9408	0.9451	0.9551	0.9775
X13	0.8458	0.8912	0.8930	0.9813	0.8506	0.9178	0.9368	0.9022	0.8999	0.9635
X14	0.7790	0.5204	0.9519	0.9874	0.9953	0.9875	0.9566	0.9838	0.2513	0.3861
X15	0.8483	0.9235	0.9525	0.4125	0.9987	0.4296	0.9928	0.5901	0.9158	0.9777
X16	0.8270	0.8224	0.8723	0.8654	0.3457	0.8482	0.9058	0.9064	0.9478	0.9821
X17	0.5972	0.5905	0.7297	0.8723	0.7825	0.9156	0.8134	0.7328	0.3613	0.5039
X18	0.7800	0.9235	0.6423	0.5386	0.4035	0.8443	0.4478	0.6088	0.2198	0.2617
X19	0.8874	0.8539	0.9599	0.9367	0.8382	0.9011	0.8675	0.8562	0.9277	0.9341
X20	0.9382	0.5927	0.4233	0.2164	0.4529	0.2264	0.8386	0.8448	0.7577	0.9613
X21	0.9226	0.9279	0.9519	0.9874	0.7825	0.8688	0.8134	0.8073	0.4790	0.2581
X22	0.8874	0.7503	0.9273	0.9367	0.8449	0.9011	0.8675	0.8562	0.9692	0.9559
X23	0.9450	0.9279	0.8886	0.9933	0.9987	0.9972	0.9119	0.9861	0.9692	0.9778

5.1.2. Dominant Factors Affecting the Vulnerability of Regional Economic Systems

The average magnitude of the influence of the detection factors in the regional economic system on the change of the vulnerability of the ecological–economic–social system in the Urumqi–Changji–Shihezi urban agglomeration is GDP per capita (X11) > the amount of social fixed asset investment (X13) > local fiscal revenue (X10) > urbanization rate (X8) > the proportion of industrial value added to GDP (X9) > total retail sales of social consumer goods (X12) > the proportion of primary industry (X17). GDP per capita, as an indicator reflecting the comprehensive strength of the economy, is the dominant factor in the regional economic system leading to the decreasing vulnerability of urban agglomerations, which is consistent with the findings of ChaoGAO et al., Liang and Xie, Lu et al., and Wang et al. [25,48,49,60]. GDP per capita is a complete manifestation of the economic capacity of supporting cities [61]. Its influence as a socioeconomic driver on the change of vulnerability of urban agglomerations is more active. The GDP per capita of the Urumqi–Changji–Shihezi urban agglomeration is on a growing trend. At the same time, the investment structure is continuously optimized. These factors are conducive to the stability of the economic system of urban agglomerations, making the urban economy more resilient [62], enhancing the risk resistance of the regional economic system, and reducing vulnerability. However, the weak economic foundation and the slow lag in regional economic development and industrial structure optimization will also restrict the degree of opening up of the regional economy to the outside world. Thus, GDP per capita will also hinder vulnerability reduction [63]. The total social fixed asset investment is an essential manifestation of economic structural vulnerability, which facilitates the effect on economic structural development [53] and has a significant positive effect on GDP. The rise of total social fixed asset investment can drive the economic improvement of the urban agglomeration of the Urumqi–Changji–Shihezi while alleviating the vulnerability of the regional economic system of the urban agglomeration.

5.1.3. Dominant Factors Influencing the Development of Vulnerability in the Social System

The average magnitude of the influence of the detection factors in the social development system on the change of vulnerability of the ecological–economic–social system in the Urumqi–Changji–Shihezi urban agglomeration is population density (X14) > per capita urban road area (X16) > per capita net income of rural residents (X21) > number of beds in medical and health institutions (X22) > average wage of on-the-job workers (X15) > number of urban primary pension insurance participants (X23) > per capita disposable income of urban residents (X20) > the number of public toilets owned (X19) > density of drainage pipes (X17) > gas penetration rate (X18), in that order. Population density and urban road area per capita are the top two factors influencing the degree of vulnerability of social systems in the Urumqi–Changji–Shihezi urban agglomeration and are the key factors contributing to its declining social vulnerability. This is different from the results of YU et al. [64], and the main reason for the difference in results is the difference in evaluation indicators. The population has a more critical role in the vulnerability of the social system in Xinjiang. However, the rapid urbanization process leads to rapid population accumulation. The peak in population also increases the vulnerability of various aspects of urban development [53]. In contrast, the data collected and compiled on population density indicators show that the population density of the Urumqi–Changji–Shihezi urban agglomeration is decreasing, which can, to some extent, alleviate the pressure brought by the social system pressure. Inadequate infrastructure planning and construction is an essential factor affecting social vulnerability [21,65]. It is consistent with the results of LIU et al. [66] in the evaluation of social vulnerability in the Yellow River Delta region; per capita urban water supply, which reflects the degree of infrastructure support, is the main barrier factor. Urban road area per capita is an important indicator of urban accessibility, a sign of the increasing improvement of urban infrastructure, which is conducive to improving the coping capacity of urban social systems [67] and positively affects the reduction of the ecological–economic–social vulnerability of urban agglomerations.

5.2. Policy Recommendations

The overall vulnerability index of Urumqi–Changji–Shihezi urban agglomeration shows a decreasing trend, and the internal development process is more stable. Overall, the vulnerability index is lowest in Urumqi city on average, followed by Shihezi city, Changji city, Fukang city, Hutubi county, Manas county, and the highest urban vulnerability index in Shawan city. In the process of urban agglomeration development, different vulnerability risks are faced by different regions. Here, this paper proposes targeted measures to reduce the vulnerability index to make theoretical guidance for the sustainable development of the ecological, economic, and social systems of the Urumqi–Changji–Shihezi urban agglomeration.

Suggestions for the overall development of Urumqi–Changji–Shihezi urban agglomeration are as follows: the main problem of the current urban agglomeration is that the urban agglomeration is still in the primary development stage, with low integration in all aspects and unreasonable spatial structure. Given the main problems currently faced by the urban agglomeration, the development of the urban agglomeration should be promoted in the following directions in the future:

(1) Promote horizontal linkage among the cities of the Urumqi–Changji–Shihezi urban agglomeration and elevate its spatial structure optimization to a new level so that the overall economic strength of the urban agglomeration can be improved;

(2) Strengthen the core city driving role. Urumqi, as the core city of Urumqi–Changji–Shihezi urban agglomeration, will continuously improve its urban functions, play its economic radiation and driving role, and drive and lead the Urumqi–Changji–Shihezi urban agglomeration;

(3) Improve the level of industrialization of agriculture and animal husbandry and promote the modernization of agriculture and animal husbandry. The counties and cities in the city cluster of Urumqi–Changji–Shihezi that are dominated by agriculture and animal husbandry are mainly Manas County, Hutubi County, Shihezi City, Wujiaqu City, etc. They should actively cultivate characteristic advantageous industries such as cotton, animal husbandry, and agricultural products processing and promote the production base of raw materials for agricultural products processing and the integration of production, processing, and marketing operations;

(4) Coordinate to undertake industrial transfer and promote high-quality development;

(5) Improve the infrastructure network and strengthen the connection between inside and outside the city cluster. Not only should we pay attention to the construction of external transportation lines; we should also improve the intra-city clusters' transportation network, such as the one-hour transportation network of the Urumqi metropolitan area and the construction of Urumqi-Changji rail transit;

(6) Improve the quality of public services and jointly promote people's well-being. Urumqi–Changji–Shihezi urban agglomeration should promote the common construction and sharing of social security, education, medical care, etc., and enhance public safety and security capacity better to meet the full needs of the people's lives.

6. Conclusions

The perspective of this paper is ecological–economic–social system vulnerability, using the integrated index method and the gray prediction model to investigate the spatial-temporal evolution characteristics and future development trends of the three systems of the oasis city cluster in the arid zone—the Urumqi–Changji–Shihezi urban cluster—and explore the main influencing factors of ecological–economic–social system vulnerability of the Wuchang Shi urban cluster with the help of geographic probes. The main conclusions are as follows:

(1) Regarding time-series changes, the overall change trend of the comprehensive vulnerability of the Urumqi–Changji–Shihezi urban agglomeration during 2009–2018 is slowly decreasing, and the vulnerability index of each system is decreasing in fluctuation. Specifically, the ecological and environmental vulnerability decreased significantly during the study period, and the regional economic vulnerability showed a changing trend of first decreasing, then increasing, and then decreasing. The change in social system vulnerability was more stable and showed a slow decreasing trend;

(2) In terms of spatial evolution, the difference in the spatial evolution pattern of the vulnerability index of the ecological–economic–social system of the Urumqi–Changji–Shihezi urban agglomeration changes from large to small, where the magnitude of change in regional economic vulnerability is small, and the magnitude of change in social and ecological environmental vulnerability is large;

(3) In terms of influence factors, the parkland area per capita, arable land area per capita, and GDP per capita, the amount of fixed asset investment in the whole society, as well as the population density and urban road area per capita, are the top two influencing factors leading to the reduction of vulnerability in the ecosystem, economic system, and social system, respectively, and are also the key influencing factors for the reduction of vulnerability in the ecological–economic–social system of the Urumqi–Changji–Shihezi urban agglomeration;

(4) Regarding future projections, the vulnerability index of ecological–economic–social systems in the Urumqi–Changji–Shihezi urban agglomeration shows a decreasing trend, and the difference in vulnerability index between systems is reduced. The vulnerability index of Urumqi city is the lowest, with 0.0721 in 2025, followed by Shihezi city, Changji city, Manas county, Fukang city, Hutubi county, and Shawan city, among which Shawan county has the highest predicted vulnerability index.

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System Dynamics Theory Applied to Differentiated Levels of City–Industry Integration in China

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Abstract: The development of city–industry integration is crucial for modern cities and is a core element of city competitiveness enhancement and sustainable development. This study considers system dynamics theory to examine city–industry integration and constructs an index system to measure the degree of integration. For this purpose, 31 regions in China (including provinces, autonomous regions, and municipalities directly under the central government) are considered as research samples. Objective evaluation methods such as factor analysis and entropy methods are applied to evaluate the target value. The research results reveal a wide gap in the levels of city–industry integration in various regions of China. Furthermore, the Middle East outperforms the Western and Northeastern regions. Accordingly, the advantages of the Central and Eastern regions should be combined, and a leading and radiation-driven role should be played. Moreover, capital investment in the Western and Northeastern regions should be increased, and emphasis should be placed on local characteristics. Moreover, urban economic development, industrial transformation, and industrial upgrading should be promoted, and the sustainable development capacity of cities should be enhanced.

Keywords: the integration of industry and city; system dynamics; the entropy method; the level of industrial and urban integration development

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1. Introduction

The urbanization level of developed countries has exceeded 75% and that of developing countries is approximately 50%. The urbanization level of China reached 63.89% in 2020, with the number of cities reaching 687. Cities, the main body of the national economy, facilitate the modernization of a country. Moreover, cities are the economic centers of regional development, thereby enhancing regional economic development and economic levels as well as the development of cities. With the acceleration of the modernization of urban construction since the 21st century, urban industries are transforming and upgrading to enhance their industrial economy and thereby promote urban development [1].

The industrial economy is an indispensable foundation of cities, and urban development plays a decisive role in industrial economic development. Furthermore, city–industry integration relates to the rational allocation of urban resources, the quality of urban residents' life, sustainable urban development, and other major issues of modern urban management. "City–industry integration" is the simultaneous and coordinated development of urbanization and industrialization, including the integration of social, economic, cultural, industrial, spatial, and other aspects. It is a new model based on the city, with industry as the guarantee. It augments urban renewal, improves service support, and enhances the spatial value of urban areas to achieve benign development among industry, city, and residents. Currently, the development model of "promoting the city with industry and promoting production with the city" is crucial for urban management as well as to realize the mutual coordination between industrial development and urban function improvement.

Cities are large human agglomerations with administratively defined boundaries and are composed of extensive housing, transportation, and communication systems. Industries are the product of the continuous development of productivity and social division of labor. Since the reform and opening up, people's lifestyles have changed dramatically. According to the National Bureau of Statistics, the urbanization rate in the eastern part of China was as high as 63.89% in 2021, 45.99% higher than the urbanization rate of 17.9% in 1978. Along with the continuous increase in the urbanization rate, problems such as the rapid reduction of arable land, urban diseases, ruination, and bubbling have also emerged. Accordingly, the concept of city–industry integration has emerged to solve the problems in the urbanization process.

City–industry integration is a strategic initiative proposed by the state to execute deep urbanization, switch the regional development mode, and prevent the phenomenon of "empty cities" and "sleeping cities". It aims to realize the return of cities from "function-oriented" to "people-oriented". The industry is the basis of urban development, and the city is the guarantee of industrial upgrading. City–industry integration can organically combine urban functions with industrial development to enhance the efficiency of urban resource allocation, clarify urban positioning, and promote industrial transformation and upgrading, thereby facilitating urban vitality and competitiveness.

Lewis developed a model of urban–rural "binary economic structure theory". The model posits that the urban–rural divide has contributed to the transfer of surplus rural labor to cities and towns, thereby augmenting the urbanization process [1]. Chenery analyzed the relationship between economic development and urbanization in more than 100 countries from 1950 to 1970 based on World Bank Statistics. The author proposed a "two-way law of mutual promotion of urbanization and economic development" [2]. Jacobs asserted in *Urban Economics* that relying on the development of urban agriculture substantially increased productivity. Industrialization causes urbanization, and urbanization results from industrialization [3].

City–industry integration is a complex systemic project [4], which can be interpreted as a return from urban functionalism to a humanistic orientation [5]. City–industry integration is mainly reflected in the unification of layout and function, symbiosis of city and industry, integration of residence and employment, interaction of production and service, and coordination of economy and environment. [6]. The "industry" of city–industry integration refers to industry and the competitiveness of the industry and the radiation-driven effect of integration with cities [7]. The "city" of city–industry integration needs to be further developed in accordance with the development of industries that promote local economic development [8]. The city–industry integration can be realized in different ways by different entities. The problem of city–industry integration is more prominent in the construction of new urban areas, which usually include high-tech development zones, economic and technological development zones, and industrial parks in cities. The construction of new urban areas has undergone the following development stages from a simple factory industrial park focusing only on spatial concentration to an industrial park focusing on industrial concentration, providing support and service to industry rather than residence. Thereafter, it has transformed into a technology park focusing on talent concentration and service for science and technology, focusing on the human residence and living facilities. Finally, it has transformed into an industrial park integrated with the city that attracts high-end industries to settle there. Simultaneously, it creates a livable environment for city–industry integration. In many cities in China, the government's pursuit of city–industry integration generally includes three levels of meaning: the establishment of a new city district with complete functions, the selection of industries that meet the future positioning and planning nature of the city, and organic integration of the new city district with the old city [9]. For some specific forms of parks, different scholars have conducted studies. Wang et al. [10] examined the level of city–industry integration of high-tech zones in major cities in China. The authors determined that high-tech zones with a higher degree of city–industry integration performed better in terms of scientific and technological innovation and economic scale. Jiang [11] compared the degree of city–industry integration of provincial-level development zones in Jiangsu Province. The authors reported that the level of economic development, economic pulling power to the city, and industrial structure of the development zones affected the degree of city–industry integration.

Zheng et al. [12] examined the National Independent Innovation Demonstration Zone in Jiangsu Province. The authors determined that high-tech zones performed better in terms of livelihood protection to promote city–industry integration but failed to attract highly educated talents to reside in the zones. Sun et al. [13] revealed three paths of city–industry integration around the plain compensation approach of value loss and judged the rationality of city–industry integration for three types of suburban development zones.

Different researchers have differently summarized the problems in the implementation of city–industry integration and have proposed corresponding suggestions. In the process of city–industry integration, new urban areas face issues such as weak service facilities, serious separation of jobs and residences, insufficient interaction between industries and cities, and imperfect functions [9]. The relevant provinces also have the problems of unscientific industrial space layouts, an insufficient supply of park infrastructure, and weak economic strength, which are not conducive to gathering industrial elements when implementing city–industry integration [14]. Accordingly, the country should strive to explore a people-centered path [15]; focus on planning, leading, and coordination; take the initiative to conduct industrial transformation and upgrading [16]; and continuously promote the integration of elements, functions, and space in the development of city–industry integration [17] to achieve the co-prosperity of industry and city in space and the symbiosis of residents and environment in function [18].

Scholars have used different methods to examine the degree of city–industry integration and have established an evaluation index system. The more commonly used methods include the analytic hierarchy process (AHP) [19,20], factor analysis and principal component analysis [21–23], entropy method [24–26], integration, coordination, and coupling degree models [27–29], four-grid quadrant method [30], and fuzzy comprehensive evaluation method [31]. Liu examined the development of the port economy and city integration in Suzhou, China, based on gray correlation analysis [32]. Given that city–industry integration implies the organic integration of industry and city in different dimensions; it is based on the system theory condition. Therefore, it is more scientific to examine the level of city–industry integration under the system theory condition and using the system dynamics approach. Currently, few studies have focused on city–industry integration by using the system theory, and most of them are only limited to exploring the operation mechanism of the city–industry integration system. The present study uses Vensim PLE Software to simulate the city–industry integration system. In addition, it uses the city–industry integration evaluation index system to empirically evaluate the city–industry integration level of 31 provinces, autonomous regions, and municipalities directly under the central government in China.

2. Methodology

2.1. Construction of the System Dynamics Model

Bertalanffy considered a system as an organic whole with certain functions formed by several elements linked in a certain structural form [33]. Systems are generally characterized by wholeness, structure, hierarchy, and relatedness. The city–industry integration system constitutes diverse, complex, and dynamic subsystems, and each subsystem is influenced by many elements. The city–industry integration system can be developed at two levels: industry and city. The industrial level is reflected by the industrial organization, structure, layout, and agglomeration, and the city level is reflected by urban resources, scale, life, governance, and so on. City–industry integration constitutes the population, environment, policy, and service systems. Through the intersection of these systems with related elements, a city–industry integration system with the characteristics of factor, function, system, population, and cultural integration is formed. In the city–industry integration system, urban development and industrial transformation and upgrading are mutually influential and jointly promote improvement. The city–industry integration system is crucial to solving the problems of "urban diseases", such as traffic congestion, housing tension, water supply shortage, energy shortage, environmental pollution, disorder, energy flow, and imbalance of input and output of material flow. Furthermore, it helps to promote and inherit the city's characteristic culture and enhance the industrial development and infrastructure construction in the city. Accordingly, city–industry integration can promote the double-driven development of the city economy and city construction. Figure 1 depicts the system diagram of "city–industry integration".

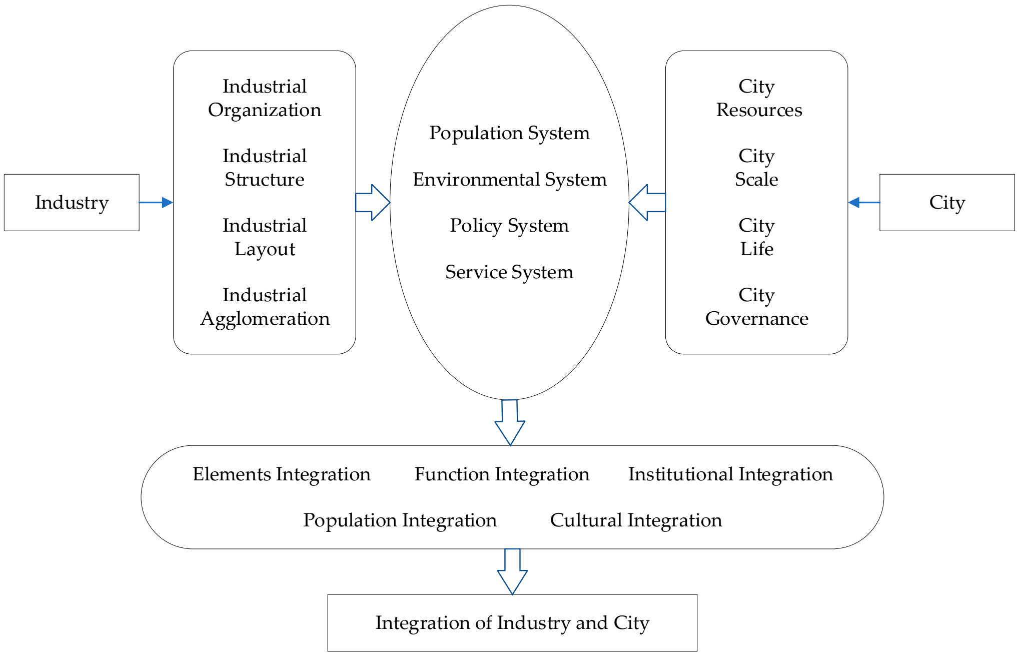


Figure 1. The "city–industry integration" system.

"Causal chains" helps examine the complexity of the city–industry integration system, given that it can reflect the relation between events. Causal networks are systems constituting several "causal chains" [34]. In this study, the Vensim PLE Software was used to simulate the cause–effect relationships among industries, cities, and the whole system to reflect the cause–effect relation between its elements. The paper was combined with related studies [35,36]. The proportion of value added by secondary and tertiary industries was selected to reflect the industrial structure. In addition, the assets of industrial enterprises above the scale and real estate fixed asset investment were selected to reflect the industrial economic situation. Moreover, the number of scientific and technological innovation personnel and the number of patents granted were selected to reflect the scientific and technological innovation situation. Several industrial enterprises above the designated size and the proportion of industrial employment were selected to reflect the industrial scale. Figure 2 presents the causality diagram at the industrial level.

Urban development is the premise of the process of the development of city–industry integration. Combined with the variables in related studies [37,38], GDP per capita, disposable income per capita, and average wage of employees were selected to reflect people's living standards. Population density was selected to reflect the city scale. Furthermore, the number of physicians per 10,000 people, number of passenger cars per capita, postal service per capita, public library collection per capita, and education expenses were selected to reflect the city's function and service level. The target of educational expenditure refers to the actual expenditure on education in the budgets of the central and local financial departments, including the personnel expenditure and public expenditure on schools of various types and at various levels, as well as the expenditure on the construction of schools and the purchase of large-scale teaching equipment. This index can well reflect the city's service function in the field of education. In addition, environmental protection expenditure was selected to reflect urban sustainable development ability. As depicted in Figure 3, the cause–effect diagrams at the city level were constructed using the aforementioned indicators.

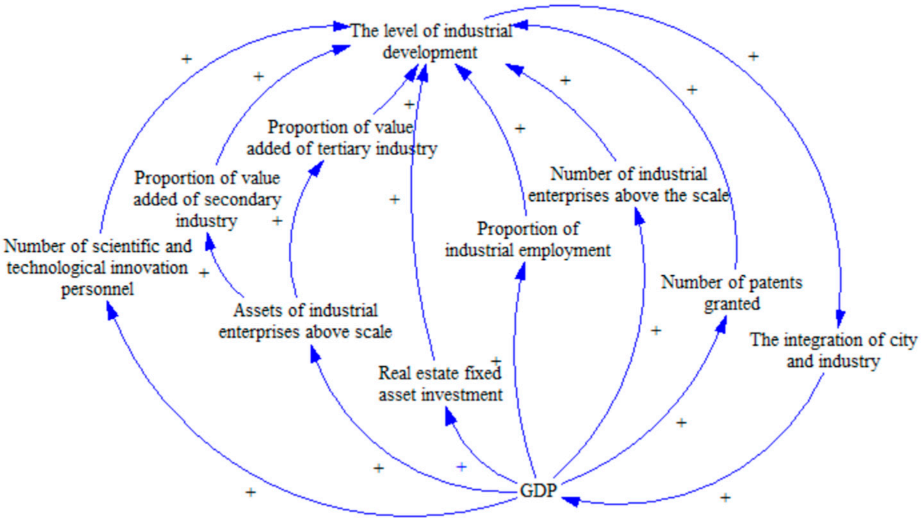


Figure 2. Industry-level causality diagram of the "city–industry integration" system.

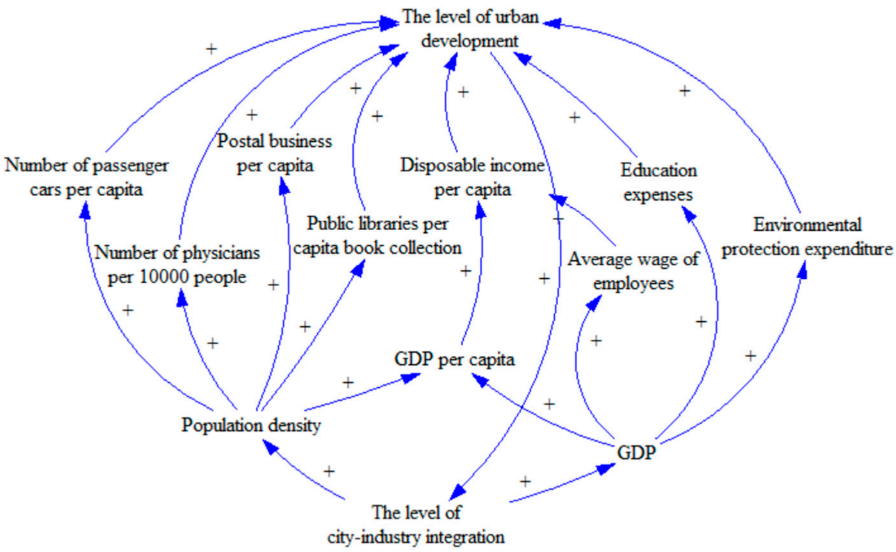


Figure 3. City-level causality diagram of the "city–industry integration" system.

Furthermore, the cause–effect diagrams at the industry and city levels were combined to obtain the cause–effect diagram of the city–industry integration system, reflecting the effect of each element at the industry and city levels in the city–industry integration system. Figure 4 depicts the causality diagram of the city–industry integration system.

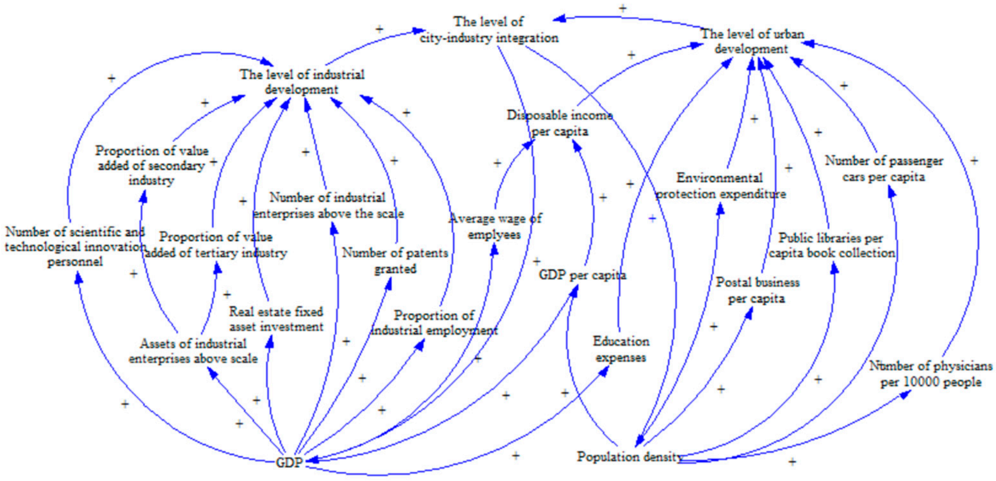


Figure 4. Causality diagram of the city–industry integration system.

2.2. Construction of an Index System

Following the scientific principles, structure, hierarchy and relevance, a multidimensional index system was constructed by considering the connotation of city–industry integration and the causal correlation between key elements of each internal subsystem, such as population, policy, environment and service systems.

Indicators were selected from industrial development and urban development to develop the indicator system. The index system comprised two primary indicators and 18 secondary indicators. Of these, eight secondary indicators were selected to reflect industrial structure, industrial economic status, industrial science and technology innovation status, and industrial scale. Moreover, 10 secondary indicators were selected to reflect people's living standards, urban scale, urban function and service level, and urban sustainable development capability. Table 1 displays the specific indicators. The relevant data are disclosed in the Statistical Yearbook of China and the Statistical Yearbook of each province. Most of the data are from the China Macro Database (CMD), China Regional Database (CRD) and China Industrial Enterprise Database (CIED), while the rest are released by the National Bureau of Statistics (NBS).

Table 1. The index system of the level of city–industry integration.

First-Level Index	Second-Level Indicators	Unit	Characteristic	Source and Reference
Industry Development Level	The proportion of value added to secondary industry	%	Positive	CMD [39]
	The proportion of value added to tertiary industry	%	Positive	CMD [39]
	Assets of industrial enterprises above the scale	Billion	Positive	CIED [40]
	Real estate fixed assets investment	Billion	Positive	CRD [40]
	Number of scientific and innovative personnel	People	Positive	CRD [41]
	Number of patents granted	Pieces	Positive	CRD [41]
	Above-scale industry number of business units	Individual	Positive	CIED [30]
	The proportion of industrial employees in active population	%	Positive	NBS [30]

Table 1. *Cont.*

First-Level Index	Second-Level Indicators	Unit	Characteristic	Source and Reference
Ubran Development Level	GDP per capita	Yuan	Positive	CMD [28]
	Disposable income per capita	Yuan	Positive	CMD [28]
	Population density	People/km^2	Centering	CRD [42]
	Number of physicians per 10,000 people	People/10,000	Positive	CRD [42]
	Number of passenger cars per capita	Vehicle/person	Positive	CRD [43]
	Postal business per capita	Billion Yuan/10,000 people	Positive	CRD [43]
	Education expenses	Million Yuan	Positive	CRD [28]
	Environmental protection expenditure	Million Yuan	Positive	CRD [44]
	Public libraries per capita book collection	Books/10,000 people	Positive	CRD [45]
	Average wage of employees	Yuan	Positive	NBS [28]

2.3. Data Processing

Dimensionless treatment for each positive indicator and consistent treatment for negative and centered indicators using the following formulas were considered to prevent the influence of different magnitudes, units, and nature of indicators.

For the positive indicator, the formula is as follows:

$$z = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{1}$$

For the inverse indicator, the formula is:

$$z = \frac{x_{max} - x}{x_{max} - x_{min}} \tag{2}$$

For the centering indicator, the formula is as follows:

$$z = \frac{1}{|x - \overline{x}|} \tag{3}$$

where z denotes the standardized index value. The population density in the index system is the central indicator, and the rest are positive indicators.

After the standardization of indicators, the values were shifted to the right by 0.0001 overall to eliminate the effect of the 0 value.

Moreover, weights are essential to combine data into one indicator according to their importance. Thus, a preferable method should be chosen to calculate the weights of each indicator. Since subjective assignment methods such as AHP need to determine the weights based on expert scores, which are somewhat subjective, the objective assignment method was chosen to determine the weights of each indicator [46]. Furthermore, a combination of factor analysis and the entropy method in the objective assignment method was selected to avoid the subjectivity of the subjective assignment method and the limitation of selecting only one objective assignment method. This approach was considered to assign weights to the indicators of the city–industry integration index system and evaluate the degree of city–industry integration in 31 provinces, autonomous regions, and municipalities directly under the central government.

Using SPSS 25.0 software, factor analysis was applied to determine the weights of seven indicators of industrial development level and 10 indicators of city level in the index system of city–industry integration to obtain the scores of the two indicators in each province. The specific steps are as follows: (1) conduct a factor analysis appropriateness test; (2) conduct a common factor ANOVA; (3) conduct factor rotation and naming; (4) and calculate the factor scores of industrial development and city development levels in each province.

3. Results and Discussion

3.1. Results of Factor Analysis

The KMO statistic of the industrial development level was 0.760, implying suitability for factor analysis. As indicated in Table 2, the characteristic roots of the first two principal components were greater than 1, and the cumulative contribution rate reached 94.248% (generally, it is considered better to have a cumulative contribution rate of more than 80%). Combined with the gravel plot, it is appropriate to take the first three principal components. Since the indicators did not indicate significant differentiation among the principal components, they were rotated. After the rotation, the first principal component had a large load on the assets of industrial enterprises, investment in real estate fixed assets, number of scientific and technological innovation personnel, number of patent authorizations, and number of industrial enterprises above the designated size. These are referred to as industrial development factors. The second principal component had a large load on the proportion of value added in the secondary industry and the proportion of value added in the tertiary industry, referred to as the industrial structure factor. The third principal component had a large load on the proportion of total industrial employment. This is referred to as the industrial employment situation factor. The seven variables were reduced to three, and the scores of each factor in each province were calculated. The three common factors were denoted as F_1, F_2, and F_3. Combined with the component score coefficient matrix in Table 3, three linear equations were established.

$$F_1 = 0.009X_1 + 0.065X_2 + 0.210X_3 + 0.199X_4 + 0.215X_5 + 0.211X_6 + 0.195X_7 - 0.023X_8 \quad (4)$$

$$F_2 = 0.501X_1 - 0.541X_2 - 0.011X_3 + 0.019X_4 - 0.095X_5 - 0.048X_6 + 0.076X_7 - 0.028X_8 \quad (5)$$

$$F_3 = 0.027X_1 + 0.067X_2 - 0.096X_3 + 0.073X_4 - 0.015X_5 - 0.041X_6 + 0.041X_7 + 0.979X_8 \quad (6)$$

X_1 denotes the proportion of value added in the secondary sector, X_2 denotes the proportion of value added in the tertiary industry, X_3 denotes the assets of industrial enterprises above the scale, X_4 denotes the fixed asset investment in real estate, X_5 denotes the number of scientific and technological innovation personnel, X_6 denotes the number of patents granted, X_7 denotes the number of industrial enterprise units above the scale, and X_8 denotes the proportion of industrial employees in active population.

Based on the cumulative contribution of the three common factors in Table 2, the final factor score equation at the level of industrial development was derived.

$$F_I = 0.594F_1 + 0.222F_2 + 0.127F_3 \quad (7)$$

The same method applies to the urban development level indicators. According to the aforementioned steps, among the 10 indicators of urban development level, the principal components with the first three characteristic roots exceeding 1 and with a cumulative contribution rate exceeding 82.347% were selected, as indicated in Table 2. After rotation, the first principal component was loaded on the GDP per capita, disposable income per capita, number of passenger cars per capita, postal service per capita, public library collection per capita, and the average wage of employees. Therefore, it was referred to as the urban quality of life factor. The second principal component is loaded on education expenditure and environmental protection expenditure. It is called the urban sustainable development factor. The third principal component is loaded on population density and the number of physicians per 10,000 people. It is referred to as the urban residents' health security factor. The three public factors are denoted as F_4, F_5, and F_6. The component score coefficient matrix in Table 3 was considered to establish three linear equations.

$$F_4 = 0.214X_9 + 0.222X_{10} - 0.109X_{11} + 0.077X_{12} + 0.136X_{13} + 0.100X_{14} - 0.094X_{15} - 0.097X_{16} + 0.213X_{17} + 0.252X_{18} \quad (8)$$

$$F_5 = -0.012X_9 - 0.030X_{10} + 0.018X_{11} - 0.047X_{12} + 0.092X_{13} + 0.191X_{14} + 0.463X_{15} + 0.446X_{16} - 0.081X_{17} - 0.168X_{18} \quad (9)$$

$$F_6 = -0.030X_9 - 0.016X_{10} + 0.639X_{11} + 0.499X_{12} - 0.037X_{13} - 0.006X_{14} - 0.054X_{15} + 0.045X_{16} - 0.018X_{17} - 0.042X_{18} \quad (10)$$

X_9 denotes the GDP per capita, X_{10} denotes the disposable income per capita, X_{11} denotes the population density, X_{12} denotes the number of physicians per 10,000 people, X_{13} denotes the number of passenger cars per capita, X_{14} denotes the number of postal services per capita, X_{15} denotes education expenses, X_{16} denotes the expenditure on environmental protection, X_{17} denotes the number of books in public libraries per capita, and X_{18} denotes the average wage of employees.

Based on the cumulative contribution of the three public factors, the final factor score equation at the level of urban development was derived as follows:

$$F_C = 0.495F_4 + 0.181F_5 + 0.148F_6 \quad (11)$$

Table 2. Explanation of total variance of industrial development level and urban development level.

Ingredients	Initial Eigenvalue			Extraction of the Sum of Squares of Loads			Sum of Squared Rotating Loads		
	Total	Percentage of Variance	Cumulative %	Total	Percentage of Variance	Cumulative %	Total	Percentage of Variance	Cumulative %
Industry Development Level									
1	4.754	59.428	59.428	4.754	59.428	59.428	4.698	58.728	58.728
2	1.773	22.157	81.584	1.773	22.157	81.584	1.816	22.699	81.427
3	1.013	12.664	94.248	1.013	12.664	94.248	1.026	12.821	94.248
4	0.195	2.435	96.683						
5	0.163	2.042	98.725						
6	0.053	0.661	99.386						
7	0.035	0.436	99.822						
8	0.014	0.178	100.000						
Urban Development Level									
9	4.950	49.505	49.505	4.950	49.505	49.505	4.378	43.782	43.782
10	1.805	18.053	67.557	1.805	18.053	67.557	2.317	23.165	66.948
11	1.479	14.789	82.347	1.479	14.789	82.347	1.540	15.399	82.347
12	0.646	6.462	88.808						
13	0.426	4.260	93.069						
14	0.237	2.373	95.441						
15	0.181	1.808	97.250						
16	0.141	1.411	98.661						
17	0.100	0.999	99.659						
18	0.034	0.341	100.000						

Extraction method: The principal component analysis was performed; components 1–8 represent industrial development level indicators, and components 9–18 represent urban development level indicators.

Table 3. Component score coefficient matrix.

	Ingredients		
	1	2	3
Industry Development Level			
The proportion of secondary industry value added	0.009	0.501	0.027
The proportion of value added to tertiary industry %	0.065	−0.541	0.067
Assets of industrial enterprises above the scale	0.210	−0.011	−0.096
Real estate fixed assets investment	0.199	0.019	0.073
Number of scientific and innovative personnel	0.215	−0.095	−0.015
Number of patents granted	0.211	−0.048	−0.041
Number of industrial enterprise units above the scale	0.195	0.076	0.041
The proportion of industrial employees in active population	−0.023	−0.028	0.979

Table 3. *Cont.*

	Ingredients		
	1	**2**	**3**
Urban Development Level			
GDP per capita	0.214	−0.012	−0.030
Disposable income per capita	0.222	−0.030	−0.016
Population density	−0.109	0.018	0.639
Number of physicians per 10,000 people	0.077	−0.047	0.499
Number of passenger cars per capita	0.136	0.092	−0.037
Postal business per capita	0.100	0.191	−0.006
Education business expenses	−0.094	0.463	−0.054
Environmental protection expenditure	−0.097	0.446	0.045
Public library collections per capita	0.213	−0.081	−0.018
Average wage of employees	0.252	−0.168	−0.042

Accordingly, the data of each province, autonomous region, and municipality directly under the central government were incorporated into the aforementioned formula to derive the industrial development level and city development level

In terms of industrial development level, a wide gap was observed between the scores of each province. Guangdong and Jiangsu were far ahead of other provinces in terms of industrial development, with a difference of more than 0.5 points from the provinces with weaker industrial development levels. Specifically, with regard to industrial development, industrial structure, and industrial employment factors, provinces with weaker industrial development levels had a larger gap in the industrial development factor. Thus, when developing industries, provinces with weaker industrial development levels should focus on investment in fixed assets and science and technology innovation, as well as actively support enterprises in their provinces to improve their overall economic strength and scale.

In terms of urban development levels, Beijing, Zhejiang, and Shanghai outperformed all other provinces. Although the difference in urban development levels among provinces was not as major as the difference in the industry, the gap was still relatively obvious and the difference in some provincial scores exceeded 0.5 points. Specifically, with regard to the urban quality of life factor, urban sustainable development factor, and urban residents' health protection factor, provinces with lower scores had a larger gap than those with higher scores in the urban sustainable development factor. Accordingly, when building cities, more emphasis should be placed on investment in education and environmental protection to improve the city's talent pool and environmental foundation to promote the city's stable and sustainable development.

3.2. Results of Entropy Weight

The entropy method is an objective weighting method. The method can more objectively avoid the interference of human factors and can reflect the importance of each evaluation index in the comprehensive index system [47]. The steps to determine the index weights using the entropy method are as follows.

First, calculate the contribution of the *i*-th individual under the *j*-th indicator ij.

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{12}$$

Second, calculate the entropy value of the *j*-th indicator.

$$e_j = -\frac{1}{lnn}\sum_{i=1}^{n} p_{ij}\ln\left(p_{ij}\right), 0 \le e_j \le 1 \tag{13}$$

Third, calculate the coefficient of variability of each indicator.

$$g_j = 1 - e_j \quad (14)$$

Finally, determine the weights of each indicator W_j.

$$W_j = \frac{g_j}{\sum_{i=1}^{m} g_j}, j = 1, 2, 3 \ldots m \quad (15)$$

In this paper, according to the aforementioned steps and the composition of each index, the entropy method was used to calculate the two main indexes of industrial development and urban development levels, resulting in F_I and F_C as weights in Table 4.

Table 4. Weighting table of industrial development level and urban development level.

Tier 1 Indicators	Weighting w
Industry Development Level F_I	0.540
Level of urban development F_C	0.460

The formula for calculating the final score of the level of city–industry integration for each province, autonomous region, and municipality directly under the central government was obtained.

$$F = 0.540F_I + 0.460F_C \quad (16)$$

3.3. Results of the Integration Level

The level of city–industry integration for each province, autonomous region, and municipality directly under the central government was calculated and ranked, as presented in Figure 5. In addition, the specific values for each region are provided in Table A1 of Appendix A.

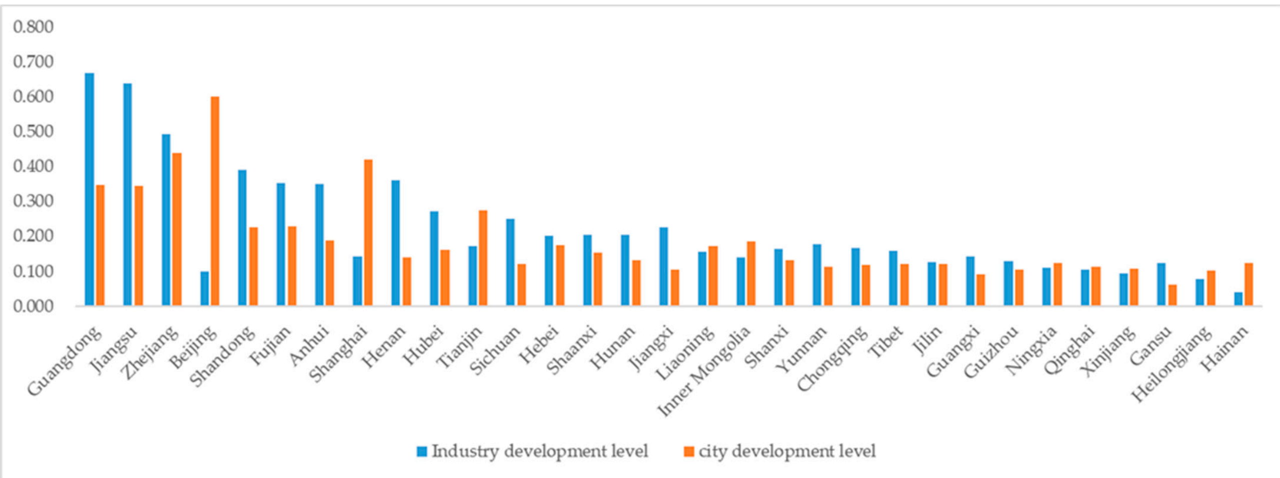
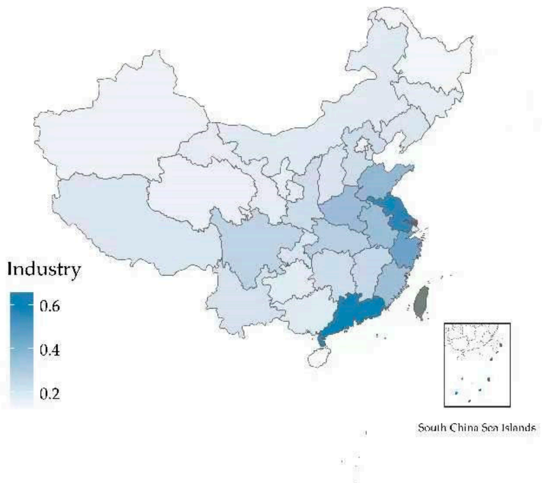
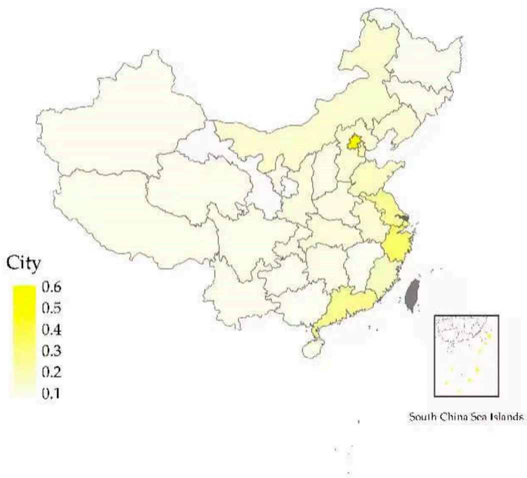


Figure 5. The total factor scores of regional industry development level and city development level.

The results of the city–industry integration level analysis indicate that Guangdong, Jiangsu, Zhejiang, Beijing, Shandong, Fujian, Anhui, Shanghai, Henan, Hubei, and Tianjin had better degrees of city–industry integration. However, Guizhou, Ningxia, Qinghai, Xinjiang, Gansu, Heilongjiang, and Hainan had large gaps compared with other provinces in terms of city–industry integration. However, the score of each province was not very high, indicating more room for improvement. Further, Figure 6 indicates that the level of city–industry integration is jointly determined by regional industrial development and urban development. On the one hand, the bar chart of different regions indicates that urban development and industrial development levels in China exhibited regional heterogeneity. On the other hand, industrial development within the same region was not consistent with the level of urban development, and one-third of the regions had a large gap between the two, further affecting the coordination of industrial and urban integrated development. Specifically, the level of industrial development in most areas was higher than that in cities. Of the regions with a higher level of urban development, Beijing, Shanghai, Tianjin, Hainan, and other regions had greater differences in the level of urban development compared with the level of industrial development. The urban development of such regions was more regulated by national policies. Although their natural resource endowment conditions were not dominant, urban development was more developed and attracted groups of talent and capital.



(**a**)



(**b**)

Figure 6. Geographical heat map of regional industrial development level and city development level. (**a**) industrial development; (**b**) urban development.

The level of city-industry integration for each province, autonomous region, and municipality directly under the central government was calculated and ranked, as presented in Figure 7. In addition, the specific values for each region are provided in Appendix A.

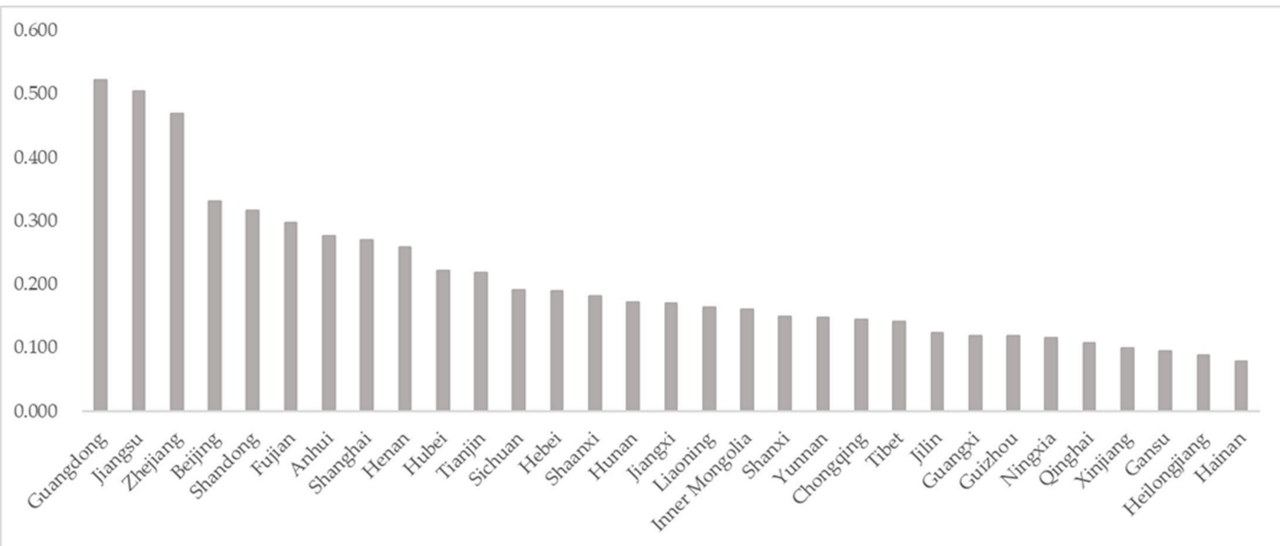


Figure 7. The level of "city–industry" integration of each region.

In order to show the results more clearly, Figure 8 displays the geographical heat map of the development level of city–industry integration.

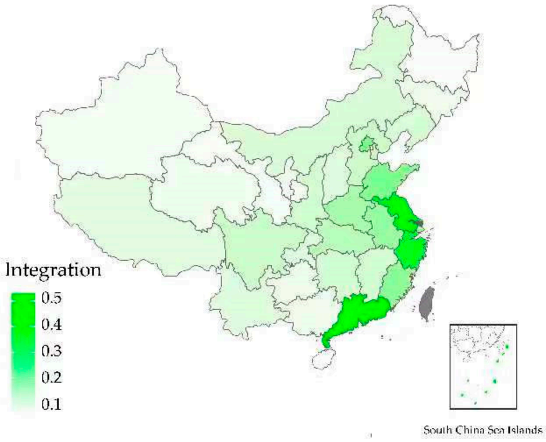


Figure 8. Geographical heat map of the level of regional city–industry integration.

In terms of the geographical location of provinces with different degrees of city–industry integration, on the whole, city–industry integration in China indicated obvious spatial distribution characteristics. Figure 8 depicts that the darker the color, the higher the fusion level. Figures 6 and 8 depict a similar distribution. However, the level of integrated development in most regions was lower than their industrial development level but higher than their urban development level. Specifically, most provinces with higher degrees of city–industry integration were concentrated in the Central and Eastern regions, and the city–industry integration in the eastern coastal regions was generally higher. The degree of city–industry integration was generally higher in the eastern coastal region, and the level of city–industry integration was generally lower in the Western region and the Northeastern region, forming a gradient spatial distribution pattern. The main reason for this pattern is that the economic development of the Central and Eastern coastal regions was generally higher. The level was generally better with a better external development pattern, and the industrial structure, scientific and technological innovation, sustainable development, and people's living standard were generally in a better state. The Western and Northeastern regions were less efficient in industrial transformation and upgrading, and the economic development was affected by the geographical location, thereby resulting in a lower level of city–industry integration. Undoubtedly, city–industry integration in the eastern coastal cities will definitely take the vanguard position in the integrated development of industry and cities in China. The eastern coastal areas will lead the in-depth development of the city–industry integration in the country in the future, given the implementation of relevant strategies for the further integrated development of domestic cities and the in-depth implementation of policies and institutions.

4. Conclusions

Based on the system dynamic model, this study identifies the causal relationship between the factors in the industrial and urban systems. For this purpose, this paper constructs an evaluation system for city–industry integration in China and measures it by combining factor analysis and entropy value methods. The development level of industrial and urban integration in China is affected by industrial development and urban development, exhibiting a decreasing east-middle-west distribution. Accordingly, the integration level needs to be improved. To sum up, industry augments urban development, and city is the platform of industrial development. The integrated development of city and industry promotes industrial optimization and upgrading and healthy urban development under the joint action of industrial production factors, economic strength, urbanization level, development environment, and other dimensions. The government should formulate different policies and strategies to improve the level of city–industry integration in each region. For the better-developed Central and Eastern regions, their advantages should be further stabilized and effective systems and economic zones should be established in city clusters or metropolitan areas to bring into play their industrial agglomeration and diffusion-driving effects, thereby leading the development direction for the surrounding areas. For the more slowly developing Western and Northeastern regions, the transformation and upgrading of industries should be actively promoted to bring into play the characteristics of regional resource endowments and low labor costs as well as to give full play to the local characteristics and ensure the development of local industries. Moreover, emphasis should be placed on the local characteristics, supply of capital should be ensured, talents in various fields should be introduced, the city should be augmented by industry, the flow and concentration of population should be promoted, the attractiveness of the region should be enhanced, and the development of city–industry integration should be promoted.

This paper combines causal chain analysis in system dynamics with factor analysis and entropy method in objective weighting method to measure and analyze the development level of industrial integration in China. Given the complexity of industry, city, and other systems, the application of a causal chain will help scholars to sort out the relation between various factors within the system. The objective weighting method can avoid the one-sidedness and subjectivity of subjective weighting, thereby reflecting the internal relationship of data. We believe that the methods applied in this paper can provide some value in the research on complex systems, especially in the research fields of innovation ecosystems, digital economic systems, and energy–economy–environment (3E). For instance, the integration of industrial digitalization and digital industrialization in the development of digital economy, as well as the integration and development of each subsystem in the 3E system.

Notably, this paper endeavors to incorporate more factors on the basis of theoretical analysis. However, many factors affect industrial development and urban development. With economic development and social progress, more factors will be included in the future. In addition, most indicators are only disclosed at the provincial level, and there is a lack of data at the township, district, and county levels. Therefore, based on the availability of data, this paper focuses on the analysis of the development level of inter-provincial city–industry integration. In the future, we aim to expand the research direction of this study and explore the factors impacting and driving city–industry integration from a mathematical perspective by building econometric models.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available as it relates to the privacy of the survey respondents and are part of ongoing research.

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Appendix A

Table A1. Ranking of provinces, autonomous regions, and municipalities directly under the central government on the level of city–industry integration.

Province	Industry Development Level F_I	Level of Urban Development F_C	Level of City–Industry Integration F	Ranking
Guangdong	0.669	0.348	0.521	1
Jiangsu	0.640	0.344	0.504	2
Zhejiang	0.494	0.440	0.469	3
Beijing	0.101	0.601	0.331	4
Shandong	0.390	0.227	0.315	5
Fujian	0.354	0.229	0.296	6
Anhui	0.351	0.190	0.277	7
Shanghai	0.142	0.420	0.270	8
Henan	0.360	0.140	0.259	9
Hubei	0.272	0.162	0.222	10
Tianjin	0.172	0.274	0.219	11
Sichuan	0.251	0.121	0.192	12
Hebei	0.202	0.175	0.190	13
Shaanxi	0.206	0.154	0.182	14
Hunan	0.205	0.132	0.171	15
Jiangxi	0.226	0.106	0.171	16
Liaoning	0.157	0.172	0.164	17
Inner Mongolia	0.139	0.185	0.160	18
Shanxi	0.164	0.131	0.149	19
Yunnan	0.178	0.114	0.148	20
Chongqing	0.168	0.119	0.145	21
Tibet	0.159	0.120	0.141	22
Jilin	0.125	0.122	0.124	23
Guangxi	0.142	0.092	0.119	24
Guizhou	0.129	0.105	0.118	25
Ningxia	0.110	0.123	0.116	26
Qinghai	0.104	0.113	0.108	27
Xinjiang	0.093	0.107	0.100	28
Gansu	0.123	0.062	0.095	29
Heilongjiang	0.077	0.101	0.088	30
Hainan	0.039	0.124	0.078	31

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Providing an Integrated Vulnerability Assessment Indicator System (VAIS) to Measure the Spatial Vulnerability of Areas near Seveso Establishments in Thessaloniki (Greece)

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Abstract: The most efficient way to reduce damage and losses in metropolitan areas with complex functions that are exposed to disaster risks is to reduce their vulnerability, which necessitates an assessment of the urban system's vulnerability. Regarding the areas located near Seveso establishments, they are characterized by high levels of vulnerability, both spatially and sectorally, as they present an increased risk due to the possible occurrence of large-scale industrial accidents. In this study, a vulnerability assessment indicator system (VAIS) that assesses the vulnerability presented in the areas located near Seveso facilities was proposed. The VAIS consisted of social, environmental and spatial indicators, and an assessment of the indicators was carried out by collecting the appropriate data. The study area is located in the western part of Thessaloniki and includes the Seveso site and the adjacent municipal districts. Prioritization of the examined municipal districts based on their overall vulnerability was carried out using multicriteria analysis methods. The results showed that there was a convergence among the three categories of vulnerability (social, environmental and spatial) in the areas that presented the highest vulnerability. The MD of Kalochori (MD7) was the most vulnerable MD in the study, while the less vulnerable ones varied depending on the vulnerability category (social, environmental or spatial) considered each time. The proposed methodology may prove to be a highly useful tool in decision-making processes when used by the relevant authorities who are qualified to define and implement a site-specific security management system.

Keywords: Seveso establishments; social vulnerability; environmental vulnerability; spatial vulnerability; multicriteria analysis; Thessaloniki

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1. Introduction

In the event of a large-scale industrial accident, there are specific factors, activities, spatial elements, groups of people, etc. that may be affected significantly and should be considered and examined thoroughly during the spatial planning processes of sites with Seveso facilities. The specific spatial elements depend on several social and environmental components of the area that will be affected by the accident, as well as the key infrastructures of the area adjacent to the facility.

Seveso sites are defined as industrial sites that, because of the presence of dangerous substances in sufficient quantities, are regulated under Council Directives 96/82/EC and 2003/105/EC, commonly referred to as the Seveso II Directive. The Directive applies to more than 12,000 industrial establishments in the European Union where dangerous substances are used or stored in large quantities, mainly in the chemical and petrochemical industry, as well as in the fuel wholesale and storage sectors. The Directive aims to control major accident hazards involving dangerous substances, especially chemicals, and contributes to the effort to reduce technological disaster risks [1]. A subsequent Seveso Directive (Seveso-III-Directive (2012/18/EU) classified industrial establishments depending on the amount of dangerous substances present, in lower and upper tiers, and the latter are subject to more stringent requirements [2]. In accordance with the European Directive 2012/18/EU [2] and the Joint Ministerial Decision 172058 (Gazette 354/B/17-2-2016) [3], the main concern for these specific areas is the adoption of measures and policies to either avoid or/and minimize the consequences for people and the environment and, by extension, for the affected area. According to the literature review, there are several case studies that assessed either the social or the environmental vulnerability of the areas with Seveso facilities but without considering their spatial vulnerability. Researchers have frequently used assessment systems and indicators of vulnerability to industrial accidents (e.g., [4–6]). In a few cases, the spatial elements were considered in light of examining the spatial dimension and spread of the accident, and not as a single multifactorial parameter, which contributed to the creation of an evaluation system for the area and the formulation of a unified spatial policy (e.g., [5,7]).

The main research question of this study focused on the elements and particularities of the areas hosting Seveso facilities that could affect and be affected by the occurrence of a large-scale industrial accident. According to the literature review and the three aspects of vulnerability (social, environmental and spatial), the elements and particularities refer to critical spatial elements such as the urban infrastructure and sensitive environmental features, as well as the socioeconomic parameters. The aim of the present study was to develop an appropriate system of indicators that can assess the vulnerability of areas hosting Seveso facilities, contributing to spatial planning and the decision-making processes as well as to the formulation of spatial policies and directions.

This study attempted to consider the spatial dimension of an industrial accident as part of a wider spatial system and investigated the concept of the vulnerability of an area that is subject to a major industrial accident by considering three aspects of vulnerability: social, environmental and spatial. The first stage of the whole process included the identification, assessment and evaluation of the risk of an industrial accident. According to the literature review and the three aspects of vulnerability, a vulnerability assessment indicator system (VAIS) that measures the vulnerability displayed by the areas located near Seveso industries was defined. The application area included the western part of Thessaloniki (the municipal districts (MDs) of Thessaloniki, Ampelokipi, Menemeni, Elefterio Kordelio, Evosmos, Diavata, Kalochori and Nea Magnisia) in Greece. The VAIS included social, environmental and spatial indicators, and an assessment of these indicators was performed through the collection of appropriate qualitative and quantitative data. Environmental, social and spatial vulnerability were considered as equally important components of vulnerability. The examined MDs were finally prioritized based on their overall vulnerability by using well-known multicriteria analysis methods (AHP and TOPSIS).

The remainder of the article is structured as follows. Section 2 describes the state of the art regarding social and environmental vulnerability, while Section 3 describes the methodological framework used for developing the VAIS and assessing the vulnerability of the examined areas (MDs). The study's findings are provided and analyzed in Section 4, while the study's primary conclusions are presented in Section 5.

2. State of the Art

The Social Vulnerability Index (SoVI) was created by Cutter et al. [8], who investigated the spatial patterns of social vulnerability to natural hazards at the county level in the United States to explain and comprehend the social burdens of risk. The Social Vulnerability Index's sensitivity to modifications in its construction, the scale at which it is applied, the set of variables applied, and the different geographic contexts were explored later by Schmidtlein et al. [9]. Their investigation served as a starting point for comprehending the social vulnerability metric's sensitivity. They showed that the algorithm was sensitive to changes in its quantitative design but robust to slight changes in the variables' composition and scale. They also highlighted the requirement for expert involvement when creating the index, considering this sensitivity.

Holland et al. [10] developed a methodology for quantifying social vulnerability to natural hazards in Norwegian municipalities. Through factor analysis, they calculated the vulnerability scores of the socioeconomic and built environment for each Norwegian municipality. The findings demonstrated that there were significant geographical differences: municipalities with high socioeconomic vulnerability were concentrated in portions of the southeast and northern half of Norway, whereas southwestern Norway was the region with the lowest socioeconomic vulnerability. Additionally, in densely populated places, the built environment's vulnerability was the greatest.

Hummel [11] assessed the hazards, social vulnerability, resilience research and the availability of spatial data in Brazil. The study examined the methods used to understand social vulnerability, risk exposure and resilience. It also examined the potential markers that could be used to gauge risk exposure and social vulnerability. For the State of Paraná, replication research on the Social Vulnerability Index (SoVI) was carried out. This allowed the creation of a comparative indicator of social vulnerability at the municipal level, demonstrating how various populations could be impacted by catastrophes.

Holand and Lujala [12] measured the ability of an existing social vulnerability index to represent social vulnerability in a different country from the one for which it was first developed. They created two variants of the Social Vulnerability Index developed by Cutter et al., 2003 for Norway. The first one replicated the original index as closely as possible (SoVI Replica), and in the second, they performed various adjustments (SoVI Adapted). The findings indicated that only 19% of the variation in the adapted index was explained by the replicated index. Therefore, there were significant variations between analyses that simply replicated the index and those that customized it for a new situation.

Siagian et al. [13] attempted to quantify, identify and map the variations in the social vulnerability of Indonesian districts to natural hazards through the use of the social vulnerability index (SoVI) methodology. According to their results, "socioeconomic status and infrastructure", "gender, age, and population growth" as well as "family structure" were the three key determinants of social vulnerability in Indonesia.

Flanagan et al. [14] discussed the creation of an SVI for use in disaster management and examined its potential utility by using Hurricane Katrina's effects on the local people as an example. The SVI's foundational dimensions included socioeconomic status, household composition and disability, minority status and language, and housing and transportation. The Katrina case study demonstrated how the SVI could be used in the response and recovery stages as a factor in estimations of risk. Older people were especially at risk during this incident. Additionally, regions that took longer to recover included those that had severe flooding and those with populations who were socioeconomically fragile.

Fatemi et al. [4] investigated the crucial parameters for determining the degree of risk of people residing close to chemical sites. They created and evaluated several indicators using the Fuzzy Delphi method (FDM) and the Fuzzy Analytic Hierarchy Process (FAHP). Thirty-five relevant experts participated in the study, and the indicators of human vulnerability were investigated in two sets of social and physical domains. According to the FDM and FAHP, population density, the vulnerability of certain groups, and awareness were the top three indicators of human vulnerability.

According to Flanagan et al. [15], social vulnerability is defined in terms of a person's or community's capacity to foresee, deal with, repair and recover from the effects of a disaster. Socioeconomic status, household composition, minority status and access to vehicles were all considered in their study as primary factors that might affect a person's social vulnerability.

A methodology for estimating the risk of technological hazards, which included two steps, was proposed by Sanchez et al. [7]: (i) the processing of meteorological databases to determine the study's most likely and conservative scenario, and (ii) applying a local social vulnerability index to categorize the population. A potential release of liquefied ammonia from a meat-packing plant in the city of La Plata, Argentina, was given a risk estimate. The technique entailed combining the layer of the sociodemographic classification of the impacted population with the simulated toxic threat zone and Areal Locations of Hazardous Atmospheres (ALOHA) software. The findings highlighted the regions where there was a greater danger of exposure to ammonia, which should be addressed to prevent disasters in the area.

Tahmid et al. [5] created a model for calculating the risk and sensitivity of humans to chemical mishaps. A GIS-based methodology that models accidents and determines the population's susceptibility by using computer-aided hazard modeling tools and technical guidelines was proposed. A set of societal indicators gathered from pertinent research, expert judgments and the World Bank's recommendations was used to estimate the population's susceptibility. The Meghnaghat Industrial Area in Bangladesh was used as a case study. The vulnerability map and hazard footprints were superimposed to create a risk map, which was used to evaluate the current land use and provided suggestions for future land use planning.

A novel approach was provided by Botezan et al. [16] to examine if changes in urban territorial dynamics had a significant impact on social vulnerability. Within the Urban Atlas inventory, the technique discovered and selected three case studies that best reflected the dynamics of significant Romanian cities, taking the following dangers into account: earthquakes, flood, and technological risks. The findings indicated that significant changes in land use were associated with a transition from low susceptibility to highly sensitive areas as a result of the growth of urban areas at the expense of natural and agricultural areas.

Regarding the environmental dimension of vulnerability, there have been just a few investigations.

Through two case studies (the municipality of Omegna and the province of Turin in Italy), Demichela et al. [17] analyzed and considered the administrative and practical concerns related to the implementation of the land use planning criteria at a local level, with a focus on the decisional approaches adopted, the data required to support a decision, and the merging of land use planning criteria for high-risk installations, as discussed and applied in previous case studies (e.g., [18–21]), with the local planning regulations. The investigation revealed that the "Guidelines for the Assessment of Industrial Risk in Land Use Planning" must be applied by using a multidisciplinary approach, but local governments are frequently underequipped to conduct this type of multilevel analysis because they lack the financial, human or even technical resources required. Because of this, the significance of proper urban and land design in the vicinity of high-risk facilities may be underestimated.

In their study, Sikovora et al. [22] outlined the legal reference setting in the Czech Republic and Italy, while considering the Seveso framework's environmental domain and the ongoing problems related to other legislative directives and classification adjustments. The deployment of a framework for the implementation of the Seveso Directive for the prevention of environmental effects was initially provided, along with a statistical review of environmental accidents in these two countries. The development and application of a methodological approach focusing on environmental risk assessments within the Seveso framework was then applied to a real-world Czech case study. The results showed that the Seveso Directive's environmental risk assessment was still a developing field of study that generated new issues for in-depth discussions.

Finally, in their study, Burdea et al. [6] introduced an approach that evaluated the level of risk at a site subjected to the Seveso II Directive by considering security management as well as security measures. Four indexes were created to achieve this goal: (i) the hazard's source (the establishment), (ii) the hazard's flow (the mechanism by which the accident spreads), (iii) the vulnerability of the targets (people, the environment or equipment) and (iv) safety management (prevention and protection actions). The combination of the aforementioned parameters could provide the level of risk in order to characterize the risk generated by an industrial plant in its environment and thus could highlight preventive and risk minimization measures.

3. Materials and Methods

The objective of this research was to identify and propose an appropriate system of indicators, the Vulnerability Assessment Indicator System (VAIS,) which would assess the vulnerability of areas in proximity to Seveso sites. The methodological steps for the deployment of the VAIS are shown in Figure 1. Each methodological step is thoroughly described in the following sections.

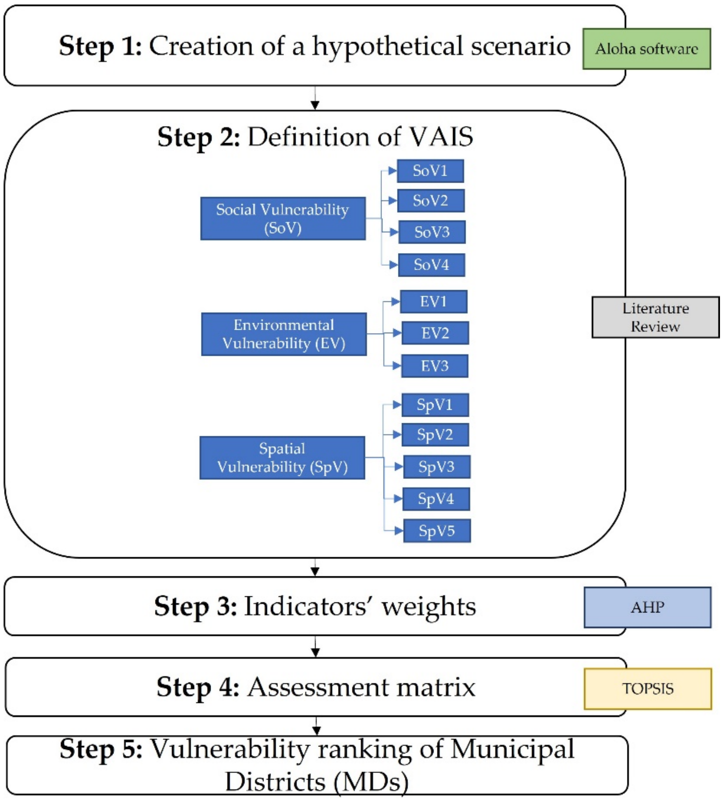

Figure 1. Proposed methodological framework.

3.1. Creation of a Hypothetical Scenario

Since the proposed indicator system is catered towards areas that are in proximity to Seveso industrial facilities, it is important to define the study area based on the sphere of influence of a hypothetical accident scenario. In the event of an industrial accident, Seveso facilities have severe impacts both within their facilities and on the adjacent activities due to the peculiarity of the raw materials used or stored during the production process. Therefore, the spatial range of such an accident is considered as an important factor in determining the vulnerability of the adjacent areas.

The first step of the proposed methodology includes the creation of a hypothetical scenario of an industrial accident and delineation of the area that could potentially be affected.

The wider area of western Thessaloniki was considered to be the case study as it is an area adjacent to a Seveso site (according to the corresponding Seveso Directive) and includes an agglomeration of high-risk industrial facilities. It is important to note that this area happens to include significant natural protected areas such as the Axios Delta estuary, complex water ecosystems, national parks, etc. In addition, it is an area with certain socioeconomic characteristics (i.e., low income, high illiteracy rates, etc.) that, according to [12–14], make up a highly socially vulnerable profile.

After recording existing industrial facilities and, given the readily available data necessary to stage an industrial accident, a hypothetical accident scenario was developed, that led to the precise definition of the study area.

The estimation of the risk for an industrial accident was carried out using Aloha software [23]. The potential zone of influence of the accident was determined by the software itself, based on user-defined inputs that included:

i. The number of installations in an industrial plant;
ii. The type and characteristics of the plant's facilities;
iii. The raw and produced materials used within the industrial plant;
iv. The climatic and topographical conditions.

During the risk assessment there were several individual scenarios that were examined in order to choose one. In several cases the lack of data led to the adoption of assumptions, such as the location where the hazardous substances were stored, the volume and conditions (i.e., air pressure) of the stored materials, the climatic conditions, etc. The purpose of this step of our work was not to replicate an industrial accident with accuracy but to define the affected area in order to apply the proposed indicator system. Based on the abovementioned assumptions, several scenarios were developed and the most realis-tic one that highlights the immediate and adjacent affected areas was selected.

The selected hypothetical scenario was assumed to take place in a cylindrical tank of size 30 m diameter and 9 m height. The estimated capacity of the tank was 6362 cubic meters with 80% fullness in gasoline. Gasoline was assumed to be in liquid form under pressure.

The accident was caused by a hypothetical failure in the tank environment that led to the expansion of the liquid and an explosion (Boiling Liquid Expanding Vapor Explosion (BLEVE) phenomenon). As for the ground weather conditions, it was assumed that there was a northwesterly wind of 10 m/s, the temperature was 38 degrees Celsius (average temperature in midday August) and the average humidity was 50%.

3.2. Delineation of the Study Area

For defining the study area, the following issues were considered:

i. The spatial extent of the risk zones from the occurrence of the (hypothetical) industrial accident, as determined by Aloha software;
ii. The allocation of the other industrial facilities subject to the Seveso Directive in the adjacent area;
iii. The spatial level at which the critical demographic, social and economic data were available.

The majority of the area located within the Aloha risk zone met the abovementioned criteria. However, a critical aspect that determined the final delineation of the study area was the availability of the statistical data needed for calculating the social vulnerability indices. Since statistical data were not available at the block level, the proposed spatial unit of analysis was the municipal districts with a significant part/area located within the Aloha risk zones.

In addition, areas fulfilling the following criteria were also included in the study area:

i. Adjacent municipal districts that were marginally affected by the accident event but, at the same time, had several Seveso facilities allocated within their administrative limits;
ii. Adjacent municipal districts containing critical transport infrastructure, such as port and railway facilities;
iii. Adjacent municipal districts that were marginally affected by the accident event but contain important environmental assets within their administrative limits. All environmentally and culturally protected areas as well as aquatic environments were considered as important environmental assets, which were considered as a multiplier factor for causing further contamination and negative effects on the environment.

The final study area to which the proposed indicator system was applied is shown in Figure 2.

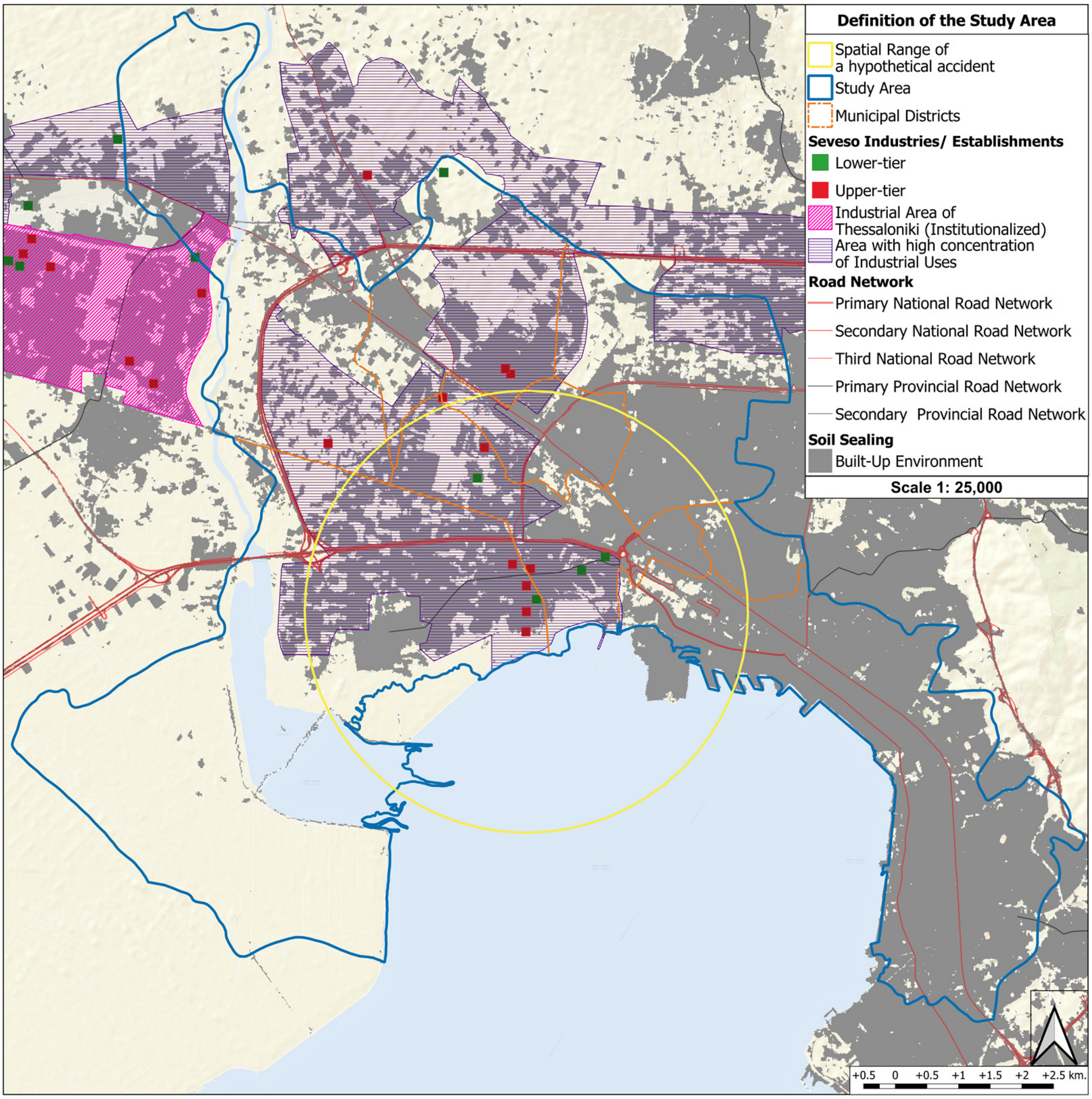

Figure 2. Delineation of the study area.

3.3. *Definition of Indicators*

To establish the indicator set, a literature review was performed to determine how to define vulnerability indicators as well as the components and factors affecting the vulnerability of an area. Several studies were examined to establish an indicative list of vulnerability assessment indicators. The proposed VAIS was based on [4–7,9,14–17,22]; data availability was also considered for the formulation of the final list.

The literature review indicated that there are four main criteria that should be considered when determining a vulnerability indicator set: (i) the spatial range of the accident, (ii) the socially vulnerable groups residing in an area with Seveso establishments, (iii) the environmentally vulnerable areas that will be affected and (iv) the infrastructure for which the operation is critical during an accident. On the basis of these criteria, three thematic vulnerability categories were identified: social vulnerability, environmental vulnerability and spatial vulnerability. For each one of these three vulnerability categories, specific quantitative and qualitative indicators were identified.

3.4. Attributing Weights to the Indicators

Given the diversity of the indicators identified in the previous step, which may include quantitative/qualitative variables and indicators, percentages and integers, and qualitative classifications of the variables etc., a ranking of their importance in the composition of the three thematic vulnerability categories was necessary. The ranking was achieved by assigning weights to each indicator under consideration for each thematic index.

To assign weights to the indicators, the Analytic Hierarchy Process (AHP) was applied [24,25].

Prof. Thomas L. Saaty initiated the Analytic Hierarchy Process (AHP) in 1977 [26]. The AHP method has been extensively used in numerous fields to define and analyze user preferences across a wide variety of areas of application as well as to solve complex decision-making challenges.

The three steps of the approach are as follows:

Step 1: Creation of an nxn matrix, where n is the number of elements compared. The relative values in the matrix are based on pairwise comparisons of each element with the others. Saaty's fundamental scale (1–9), which is used for the comparisons, is a nine-point binary comparison scale where 1 is "equally important", 3 is "slightly more important", 5 is "much more important", 7 represents "demonstrated importance" and 9 represents "absolutely more important." The index ratings are 1/3, 1/5, 1/7 and 1/9 if the relation of importance is reversed. In the pairwise comparison, the intermediate values of 2, 4, 6 and 8 can also be used.

Step 2: Normalization of the nxn matrix by dividing each value by the total sum of the vertical column to which it belongs.

Step 3: Calculation of the priority vector or weight by averaging the normalized values of the corresponding horizontal row.

Pairwise comparisons are based on the subjective judgment of the decision-maker. Checking the consistency of the comparison matrix and calculating the consistency index (CI) (Equation (1)) and consistency ratio (CR) (Equation (2)), which rate the consistency of the judgements, are important for determining the decision's validity.

$$CI = \frac{\lambda max - n}{n - 1} \quad (1)$$

where the value λmax corresponds to the sum of the elements of the column of each criterion of the nxn matrix with the corresponding priority vector, and n is the number of evaluation criteria.

$$CR = \frac{CI}{RI} \quad (2)$$

where RI is the random consistency index; its value depends on the size of the matrix (nxn) [27]. The results are acceptable and reliable when the consistency ratio (CR) is less than 0.1 ($CR \leq 0.1$).

In our study, the pairwise comparisons were based on: (i) the ranking of different indicators and variables from the literature review (e.g., [4,5,17,22]), and (ii) the critical perceptions of the authors.

3.5. Assessment Matrix

The main objective of this step was to determine the overall vulnerability of an area (spatial unit) based on the three vulnerability categories (social, environmental and spatial). To assess the vulnerability levels of each spatial unit, the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) method was used [28,29]. The results of this stage contributed to the ranking of the spatial units of the study area according to their overall vulnerability level.

TOPSIS is a straightforward and computationally efficient technique for selecting the best solution from a set of alternatives, taking a set of predefined criteria into account [25]. The method's core idea is that the chosen solution must be as close as possible to the most desired value (ideal solution) and as far away as possible from the least desired value (the non-ideal solution). Priority can be given to alternative solutions on the basis of a comparison of the relative distance to the most and least desired values.

The following steps were followed to apply TOPSIS [28,29].

After we had defined the initial assessment matrix, which consisted of n alternatives (spatial units) and m criteria (indicators), the approach involved the following five steps. The intersection of each alternative with each criterion is shown by x_{ij}:

Step 1: Normalization of the initial assessment matrix.

Equation (3) was used to normalize each element of the original evaluation matrix.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{3}$$

where i = 1, ... ,n is the number of alternatives, and j = 1, ... ,m is the number of criteria:

Step 2: Calculation of the weighted normalized decision matrix.

Equation (4) multiplies the weights of each criterion by the weights of the normalized values of the alternatives to provide the weighted normalized decision matrix.

$$v_{ij} = w_j * r_{ij} \tag{4}$$

where w_j is the weight of the j-th assessment criterion.

Step 3: Determination of the ideal (S^+) and the non-ideal (S^-) ideal solutions using Equations (5) and (6), respectively [30].

$$S^+ = \{v_1^+, \ldots, v_m^+\} = \{(max\, v_{ij} | j \in J'),\ (minv_{ij} | j \in J'')\} \tag{5}$$

$$S^- = \{v_1^-, \ldots, v_m^-\} = \{(min\, v_{ij} | j \in J'),\ (maxv_{ij} | j \in J'')\} \tag{6}$$

where J' is used for the benefit criteria and J'' is used for the cost criteria.

Step 4: Computation of the Euclidean distance of the alternatives from the ideal and the non-ideal solutions, using Equations (7) and (8) as follows:

$$S_i^+ = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^+\right)^2} \tag{7}$$

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^-\right)^2} \tag{8}$$

Step 5: Calculation of the relative closeness (C_i^+) of each alternative to the ideal and the non-ideal solution through Equation (9).

$$C_i^+ = \frac{S_i^-}{S_i^+ + S_i^-} \tag{9}$$

A value close to 1 indicates a spatial unit with fewer vulnerability issues within the specific vulnerability category, while a low relative closeness coefficient indicates a more vulnerable spatial unit.

Step 6: Ranking the alternatives based on the order of preference (the value of the relative closeness C_i^+) for each one of the three vulnerability categories.

4. Results and Discussion

4.1. A Short Profile of the Study Area

The proposed indicator system was applied in the west area of the city of Thessaloniki. Thessaloniki is the second largest city in Greece (after Athens) and is one of the largest urban centers in the Balkans. Administratively speaking, the county of Thessaloniki, the largest part of which now constitutes the metropolitan area of Thessaloniki, is divided into 14 municipalities, 4 of which compose the study area. The study area covers the historic center and the western inner and outer zone of the city, with 669,326 inhabitants, accounting for 64% of the county's population [31]. If we exclude the central–historic municipality of Thessaloniki, the rest of the study area is inhabited by mostly working-class citizens with cheap and poor-quality housing [32]. In addition, this area has a concentrated (more than the county's average) immigrant population that can be up to 5.6% of the total population of the study area. In terms of the education level, the study area has, relative to the rest of the county, low literacy rates (only 21% finished primary school and 15% have an undergraduate degree, according to the 2011 Census Count). In terms of unemployment, this area has relative high unemployment rates of up to 12% [31].

The city of Thessaloniki is an international transport node. It is connected to the two major trans-European transport networks (PATHE and Egnatia Motorway) and is a node for all major national and international rail lines. The study area includes critical transport facilities such as the commercial and passenger port and train stations. The spatial pattern of the main economic activities is dominated by industry, including clusters of wholesale, commercial and transport services located at the western edge of the study area. The study area includes a concentrated industrial zone as well as scattered industrial facilities. Agriculture is also an important economic activity in the southwest part of the county, which belongs to the large basin of Central Macedonia. Thessaloniki has some very important natural ecosystems, including the Axios Plain and the Axios–Gallikos–Loudia Delta within the study area.

4.2. VAIS

In line with the literature review, the proposed system of indicators comprised three vulnerability dimensions: social, environmental and spatial. Each of the vulnerability categories included several sub-indicators, a description of which is presented in Table 1. It should be noted that the final list of indicators was determined by the literature review and the availability of the data.

Table 1. Proposed VAIS.

Vulnerability	Indicator	Variable	Indicator Type	Units	Data Sources
Social vulnerability (SoV)	Nationality—Language (SoV1)	Percentage of population with a nationality other than Greek in the total population * [4,5,9,15]	Quantitative	Percentage of the population	[33]
	Age (SoV2)	Percentage of the population aged 0–4 in the total population * [4,5,9]	Quantitative	Percentage of the population	[33]
		Percentage of persons aged 65+ in the total population * [4,5,9,15]	Quantitative	Percentage of the population	[33]
	Education level (SoV3)	Percentage of illiterate people in the total population * [4,5]	Quantitative	Percentage of the population	[33]
	Economic status (SoV4)	Unemployment rate [4,7,9,15]	Quantitative	Percentage of the population	[33]
Environmental vulnerability (EV)	Protection status (EV1)	The MD's "Absolute Protected" area within the spatial range of the accident out of the total accident area [17]	Quantitative	m^2	[34]
		The MD's NATURA sites within the spatial range of accident out of the total accident area [17]		m^2	[34]
		The MD's natural wildlife sanctuary areas within the spatial range of the accident out of the total accident area [17]		m^2	[34]
		The MD's natural park areas within the spatial range of the accident out of the total accident area [17]		m^2	[34]
	Water resources (EV2)	Proximity to critical water bodies such as seas, lakes, wetlands, rivers and aquaculture [6]	Qualitative	-	[34]
	Flood zones (EV3)	Percentage of the flood zone within the accident area per municipal district [16]	Quantitative	m^2	[34]
Spatial vulnerability (SpV)	Spatial range of the accident (SpV1)	The area of the MD within the spatial range of accident out of the total accident area Researchers' perceptions combined with Greek legislation, such as the "Technical Specifications of Special Urban Development Plans" (FEK 510/b/2022) and the "Defining Rules, Measures and Conditions for Dealing with Risks from Major Accidents" (FEK 354/b/2016)	Quantitative	m^2	Scenarios developed with Aloha software
		Allocation of Seveso facilities Evaluation of the domino effect and the possibility of the accident's hazard range expanding; the existence (or otherwise) of a Seveso facility and its hazard level Researchers' perceptions combined with Greek legislation derived from the "Technical Specifications of Special Urban Plans (Government Gazette 510/b/2022)" and the "Defining Rules, Measures and Conditions for Dealing with Rrisks from Major Accidents" (Government Gazette 354/b/2016)	Qualitative	Number of industries	Scenarios developed with Aloha software
	Urban environment (SpV2)	Population density [4,16]	Quantitative	Persons/m^2	[34]
	Education facilities (SpV3)	Number of primary and secondary institutions Researchers' perception combined with Greek legislation (FEK 510/b/2022 and FEK 364/b/2016)	Quantitative	Number of schools	[34]
	Health facilities (SpV4)	Number of public and private hospitals and other health facilities Researchers' perceptions combined with Greek legislation (FEK 510/b/2022 and FEK 364/b/2016)	Quantitative	Number of hospitals	[34]
	Critical facililities (SpV5)	Ports, train stations, depots, transport infrastructure etc. Reseearchers' perceptions combined with Greek legislation (FEK 510/b/2022 and FEK 364/b/2016)	Qualitative	Number of facilities	[34]
		Road network hierarchy Researchers' perceptions combined with Greek legislation (FEK 510/b/2022 and FEK 364/b/2016)	Qualitative	-	[34]

* The total population is considered to be the population of the unit of spatial analysis (i.e., municipal district).

The final list of indicators included four SoV, three EV and five SpV indicators.

4.3. Indicators' Weights

As mentioned in Section 3, the importance of each indicator over the others was established and quantified using Saaty's scale through pairwise comparison of the indicators. The results of the computation process described in Section 3.4 are presented in Figure 3. It should be noted that the computation of CR (Equation (2)) was lower than the limit of 0.1 for SoV, EV and SpV, and was used to confirm the consistency of the pairwise comparison matrices.

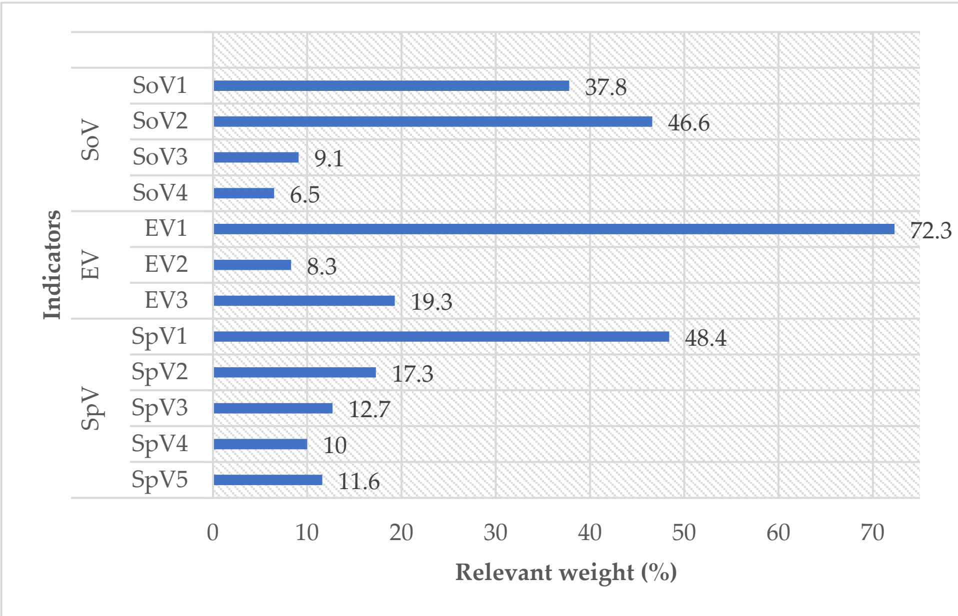

Figure 3. Relevant weights of the indicators.

From Figure 3, it can be seen that the relative weights of SoV2, EV1 and SpV1 had the largest values (equal to 46.6%, 72.4% and 48.4%, respectively, of SoV, EV and SpV), indicating that the age of the population, the environmental protection status and the accident's spatial range were the most important indicators for determining the vulnerability ranking of the MDs in the study area.

Regarding SoV, the indicator SoV2 was next, with a relative weight equal to 46.6%, while the rest of the indicators, in decreasing order of priority, were ranked as follows: SoV3 and SoV4. Thus, educational level and economic status did not contribute significantly to the vulnerability ranking of the MDs.

Continuing with EV, the rest of the indicators, in decreasing order of priority, were ranked as follows: EV3 and EV2. Therefore, proximity to critical water bodies and the percentage of the flood zone within the accident area per municipal district contributed slightly (27.6%) to the vulnerability ranking of the MDs.

Regarding SpV, the indicator SpV2 was ranked second, with a relative weight equal to 17.3%, while the rest of the indicators were ranked as follows, in decreasing order of priority: SpV3, SpV5 and SpV4. It should be noted that the relative weights of SpV1, SpV2 and SpV3 corresponded to 78.4%, and therefore the vulnerability of an MD strongly depends on the accident's spatial range, the population density and the number of educational facilities.

4.4. Vulnerability Ranking of the Municipal Districts

The ranking of the MDs for each of the vulnerability components, based on the relative closeness (C_i^+), is shown in Table 2.

Table 2. Ranking of the spatial units based on the relative closeness coefficient.

Spatial Unit	SoV		EV		SpV	
	C_i^+	Ranking	C_i^+	Ranking	C_i^+	Ranking
Thessaloniki (MD1)	0.625	2	0.886	5	0.207	6
Ampelokipi (MD2)	0.605	3	0.976	2	0.636	1
Menemeni (MD3)	0.537	6	0.742	7	0.184	7
Evosmos (MD4)	0.723	1	0.935	4	0.332	4
Elefterio Kordelio (MD5)	0.600	4	0.882	6	0.319	5
Diavata (MD6)	0.269	8	1.000	1	0.593	3
Kalochori (MD7)	0.411	7	0.000	8	0.139	8
Nea Magnisia (MD8)	0.543	5	0.945	3	0.604	2

The application of TOPSIS for the social vulnerability indicator system highlighted that the MDs of Diavata and Kalochori (MD6 and MD7) were the most socially vulnerable ones, with MD6 in first place in the column. On the other hand, the MDs of Evosmos and Thessaloniki (MD4 and MD1) emerged as the least socially vulnerable areas in the case of a major accident. If we take the weights assigned to each indicator alongside the characteristics of MD6 into account, as indicated by indicators' values in the assessment matrix, it can be concluded that the application of TOPSIS highlighted what was also observed in the analysis. Similarly, in the case of MD4, the TOPSIS results verified the initial findings from the calculated variables.

Regarding environmental vulnerability, Kalochori (MD7) was recorded as the most environmentally vulnerable area, while Diavata (MD6) was identified as the least environmentally vulnerable area. The results of the TOPSIS analysis were also in line with the primary data, especially considering the fact that MD7 has the most sensitive and ecologically valuable environmental elements that are expected to be affected by the occurrence of a major accident.

The following map (Figure 4) depicts the areas of environmental vulnerability in the study area. Within the accident's range, the majority of the MDs, especially the MDs of Kalochori, Menemeni, Elefterio Kordelio, Evosmos, Ampelokipi and Thessaloniki (MD7, MD3, MD5, MD4, MD2, MD1), included areas with a high flood risk. MD7, which emerged as the most environmentally vulnerable unit, includes, in addition to areas with a high flood risk, the protected area of NATURA and a natural reserve (national park). It also has a coastline where valuable wetlands are located. The MDs of Menemeni and Thessaloniki (MD3 and MD1) are also in proximity to the sea, increasing their environmental vulnerability.

In terms of spatial vulnerability, Kalochori (MD7) was recorded as the most vulnerable municipal district, while Ampelokipoi (MD2) was the least vulnerable district. The second most spatially vulnerable area was the MD of Menemeni (MD3). The results derived from the application of TOPSIS were once more in line with the calculated indicators. In particular, considering that Kalochori and Menemeni are the areas that would be directly influenced by the occurrence of an accident and that a number of Seveso facilities and critical infrastructure are located here, this classification accurately reflects the relative spatial vulnerability.

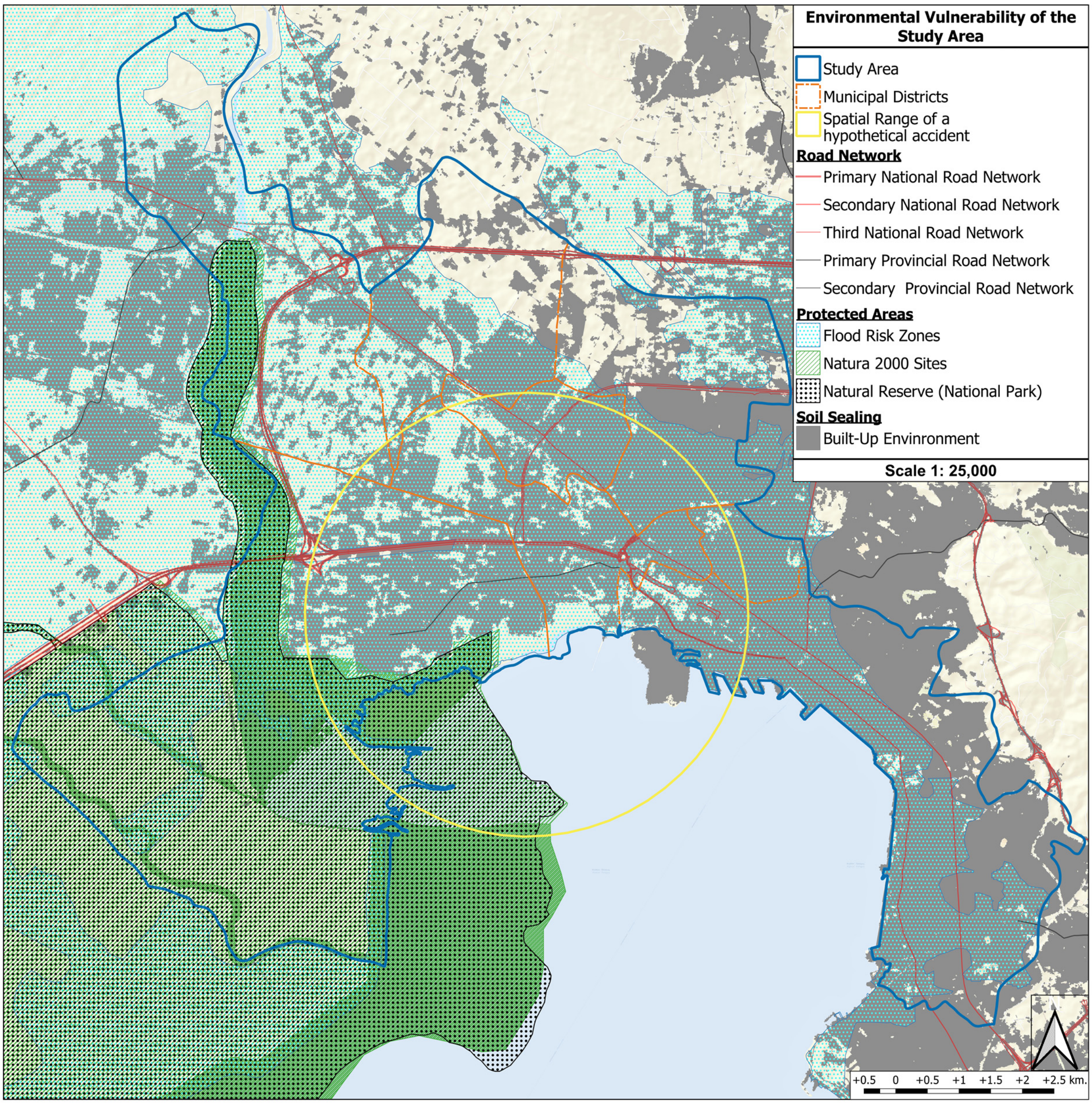

Figure 4. Areas of environmental vulnerability in the study area [35].

The following map (Figure 5) depicts the elements of spatial vulnerability. For the MDs of Kalochori and Menemeni (MD7 and MD3), which are highlighted as the most spatially vulnerable areas, it is noted that a large part of their area is located within the accident's range. In the same MDs, a substantial number of Seveso facilities are located, as well as critical elements of the transport infrastructure, such as primary roads and the rail network. The MDs of Thessaloniki and Elelefterio Kordelio (MD1 and MD5) also have a substantial amount of critical infrastructure within their jurisdiction, such as health facilities and schools, which, combined with the transport infrastructure, ranked them third and fourth in terms of spatial vulnerability.

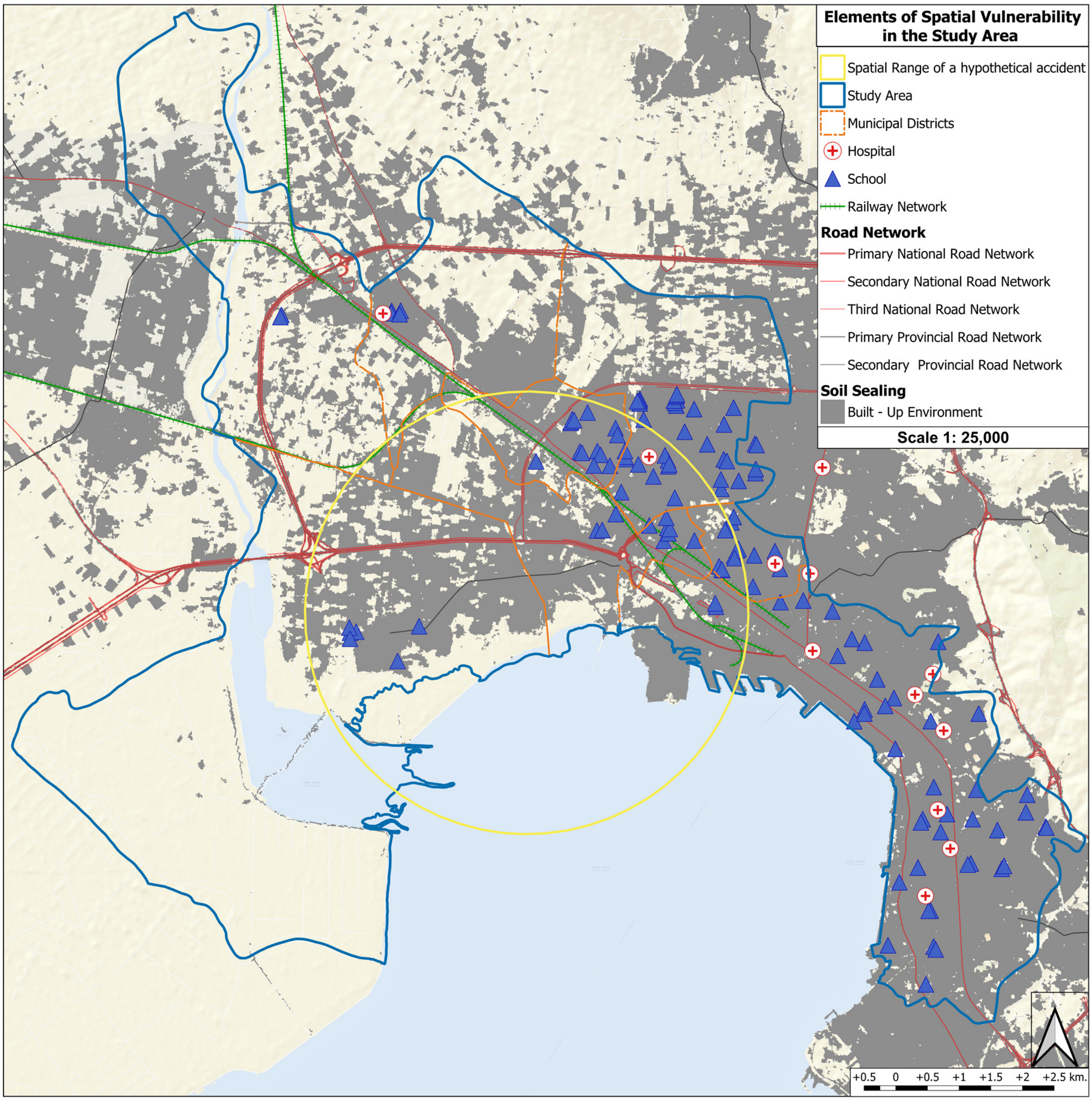

Figure 5. Elements of spatial vulnerability in the study area [35].

Based on these classification results, the MD of Kalochori (MD7) was the most vulnerable MD in the study, while the least vulnerable ones varied, depending on the vulnerability category considered. The differences in the individual vulnerability categories (social, environmental and spatial), which resulted in intermediate vulnerability rankings, were expected, especially considering the heterogeneity of the MDs within the study area.

5. Conclusions

Spatial planning can provide the context for assessing and preventing the consequences of large-scale industrial accidents. The risk of an industrial accident's occurrence, and the need to avoid, reduce and mitigate such accidents are directly linked to its spatial sphere of influence. The need to assess risk is associated with critical spatial and socioeconomic features, and risk can be seen as a key component of spatial planning policies.

This study has provided a methodological approach for deploying an appropriate set of indicators that could be used to determine the vulnerability of areas hosting Seveso facilities, contributing to spatial planning, decision-making and the creation of spatial policies and developmental trajectories.

The proposed Vulnerability Assessment Indicator System (VAIS), which measures the vulnerability of the areas located near Seveso facilities, is based on three aspects of vulnerability associated with the areas around Seveso facilities, namely the social, environmental and spatial vulnerability. Each aspect includes several indicators. Multicriteria analysis methods (AHP and TOPSIS) were used to rank the municipal districts (MDs) of the study area on the basis of their vulnerability.

According to the results, the relative weights of SoV2, EV1 and SpV1 had the largest values within the social, environmental and spatial aspects of vulnerability, respectively, indicating that the population's age, the environmental protection status and the accident's spatial range are the most important assessment indicators for determining the vulnerability ranking of MDs in the study area. In terms of the vulnerability ranking of the examined areas, there was a convergence regarding MD7, which had the highest vulnerability and therefore requires more attention during planning processes. This MD includes numerous Seveso facilities as well as a number of sensitive areas (e.g., protected areas and water bodies) that were indicated through the selected indicators of the VAIS.

This study tried to use an integrated system of indicators for assessing the vulnerability of areas near Seveso establishments. The whole methodology may prove to be a very helpful instrument in decision-making processes when used either by individuals or relevant authorities who are qualified to design and implement a site-specific security management system. It should be noted that, to the authors' knowledge, this is the first time that all three aspects of vulnerability (social, environmental, and spatial) have been considered in an integrated system of indicators.

A weakness of the proposed methodology is the lack of specific expertise and knowledge in assessing the risk of an industrial facility, and the lack of deployment of a precise hypothetical scenario of a large-scale industrial accident that could precisely identify the spatial range and the consequences of the accident, and the exact study area. In addition, the inability to access fine-grain demographic data (i.e., in building blocks) has limited a detailed evaluation of the problem and the possibility of obtaining more precise results regarding the site, the study area and the vulnerability ranking. The reliability and accuracy of the data is of utmost importance. On the one hand, the examined Seveso industrial facilities should provide an exact inventory of the hazardous chemicals; on the other, several aspects that describe the SoV, such as the demographic data, may vary from time to time, as some of the residents in industrial areas reside there temporarily. In order to implement a vulnerability-based integrated risk management approach, close cooperation among industries, regulatory bodies and the local community is required.

Further research should include (i) the formulation of various hypothetical accident scenarios in the study area and a comparison of the MDs' vulnerability rankings, and (ii) quantification of the pairwise comparisons based on the needs and specifications of the relevant stakeholders and/or policy-makers. The applicability of the VAIS and the generalizability of the results to other case studies will also enhance the reliability of the proposed methodology.

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Twenty Years of Urban Reforestation: Overstory Development Structures Understory Plant Communities in Lexington, KY, USA

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Abstract: Urban forests provide critical ecosystem services in an increasingly urbanized global landscape. The reforestation of undeveloped parcels and serially mowed grasslands can increase urban forest cover, but plant community development in planted urban forests is poorly understood. We conducted a study to elucidate the roles of time since tree planting, invasive species abundance, and other abiotic and biotic site-level factors in structuring understory plant communities within a 20-year chronosequence of planted urban forests in Lexington, KY, USA. We assessed the percent of groundcover of all understory species in fixed-radius plots on the site. Understory herbaceous plant communities demonstrated shifts from graminoid dominance to forb dominance over time, and plant communities in successively younger sites were increasingly dissimilar from that of the 20-year-old site. Invasive plant species were abundant, representing 21% of total groundcover across all surveyed plots, and became increasingly prevalent over time. Understory plant diversity was negatively associated with invasive species abundance. Overall, site factors, including time since planting, forest canopy closure, density of tree and shrub reproduction, and soil pH, accounted for much of the variability among understory communities. Understory plant communities across the chronosequence of planted sites demonstrated apparent structural shifts with overstory canopy development, but the increasing prevalence of invasive species and their negative impacts to plant diversity warrant future management to ensure the continuation of the desired successional trajectories.

Keywords: afforestation; reforestation; forest succession; rewilding; urban parks

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1. Introduction

The global population is becoming increasingly concentrated in urban areas, with 70% of the world's population [1] and 87% of the US population [2] expected to live in urban areas by 2050. Urban development is associated with a suite of negative ecological effects. Urbanization compromises soil [3,4], air [5], and water [6] quality, and elevates air [7] and water temperature [8]. Urban forests tend to be highly fragmented [9] and experience significant pressure from introduced species [10]. Urban wildlife populations often experience poor habitat quality [11] and connectivity [12], and have higher disease burden [13]. Due to impervious surface area, urban watersheds experience low infiltration and high surface runoff rates, increasing peak flow and reducing time to peak in urban streams [14]. Given the scope of these impacts and the increasing global significance of urbanization, it is imperative that we conduct new urban development more sustainably, and explore ways to improve and restore ecosystem health in existing cities.

One pathway to ecological restoration in urban areas is reforestation. Reforestation can occur naturally through the process of secondary succession, in which plant communities pass through a predictable sequence of seral stages on their way to the climax community, maintained by the given climatic and disturbance regimes [15]. In urban and peri-urban areas, this process occurs in vacant or abandoned lots [16], or abandoned agricultural fields. In addition, this process can be accelerated by planting later-successional trees that would be typical of the climax community during the initial reforestation efforts [17]. However, given the various impairments characteristic of urban areas, planted urban forests may not follow the same developmental trajectory as planted forests in more rural spaces.

The Reforest the Bluegrass program (RTB), coordinated by the Lexington-Fayette Urban County Government (LFUCG) for over twenty years in Lexington, Kentucky, USA, is an example of an effort to augment ecological restoration through tree planting. As of 2020, LFUCG reports that the program has planted over 150,000 trees in 20 sites within the Lexington urban service boundary [18]. Lexington is situated within the Inner Bluegrass physiographic province of Kentucky, USA, characterized by rolling hills and fertile soils arising from Ordovician limestone [19]. Although much of the region has been developed for agricultural or urban/suburban land-use, the vegetation community typical of the region prior to European settlement was an open woodland, dubbed the Bluegrass Savanna. This woodland was dominated by trees, such as *Fraxinus quadrangulata* Michx. (blue ash), *Quercus macrocarpa* Michx. (bur oak), *Quercus muhlenbergii* Engelm. (chinkapin oak), and *Quercus shumardii* Buckland (Shumard oak), and is thought to have been maintained by fire and grazing [20]. Understory vegetation in these savannahs included rich canebrakes (*Arundinaria gigantea* [Walter] Muhl.), native warm-season grasses, and legumes that provided valuable forage for grazing animals, including *Bison bison* L. (American bison). After the exclusion of fire and the reduced importance of grazing by bison and other large ungulates, the abundance of these precolonial ecosystems has declined. In the absence of fire, fire-intolerant species are becoming increasingly important in forests across the eastern US, restricting recruitment of species less tolerant of shade, such as the once-dominant oaks (*Quercus* spp.) and hickories (*Carya* spp.) [21,22]. This background shift in the disturbance regime is further exacerbated by ongoing anthropogenic climate change [23] and various insect and disease outbreaks [24,25], which are expected to further alter the developmental trajectory of forests in the region.

Prior to tree planting, RTB sites were serially mowed urban grasslands, and, thus, understory plant communities began as open grassland/pasture, dominated by cool-season grasses and legumes. However, as trees formed a closed canopy upon entering the stem-exclusion stage of stand development, plant communities were expected to shift over time to shade-tolerant understory species characteristic of mature forests. However, while understories of intact forest remnants in the Inner Bluegrass are often quite diverse [26], it is unclear whether, and at what timescale, these diverse understory plant communities will recover on their own in planted forest sites. As Bartha et al. [27] noted, understory plant colonization rates decline after canopy formation in old field succession, potentially limiting the ability of passive restoration to support the recovery of native plant communities. Furthermore, as Oldfield et al. [17] describe, longer-term studies are critical to understand how plant communities develop in planted urban forests over time.

While not exclusively an urban problem, invasive plants tend to be particularly problematic in urban and periurban areas [28,29]. Many plants now considered invasive were once introduced intentionally as ornamentals or as street or other landscape trees [30]. In this region, *Pyrus calleryana* Decne. (Callery pear) and *Lonicera macckii* (Rupr.) Maxim. (Amur honeysuckle) are among the most common invasive woody plants and are associated with a host of ecological impacts [31,32]. While both *Lonicera maackii* and *Pyrus calleryana* are important in our study sites, this paper is focused on non-tree-forming and shrub-forming species, such as *Euonymus fortunei* [Turcz.] Hand.-Maz (purple wintercreeper) and *Alliaria petiolata* [M.Bieb.] Cavara and Grande (garlic mustard). Still available for sale in nurseries [33], *Euonymus fortunei* is a trailing vine that forms a dense mat on the forest floor. *Euonymus fortunei* possesses adaptations, such as extended phenology [34] and animal-assisted seed dispersal [35], that help it outcompete native flora [36]. Intentionally introduced as an herb in the 1800s, *Alliaria petiolata* produces allelopathic and anti-herbivory compounds and further benefits from the absence of natural predators, early phenology, and high reproductive output [37], which aid in its outcompeting of native flora [38].

Thus, while urban reforestation is of great interest for alleviating the negative ecological effects of urbanization, forest development on these sites over time is not well understood. Because urban forests are particularly vulnerable to invasive species, plant communities in planted urban forests may not develop similarly to non-urban sites, and ongoing management focused on understory plants may be required to assist community recovery. This study evaluated plant communities in planted forests in Lexington, KY, USA, focusing on three research questions: (1) to what extent does understory plant diversity change with the time since tree planting?; (2) how do non-native invasive species influence the structure of the understory plant community?; and (3) how do forest development and other site-level factors shape understory community assemblages? Plant communities were characterized by visually assessing groundcover of all plants not forming trees or shrubs in fixed-radius plots in each of the twenty planted urban forests planted between 1999 and 2019.

2. Materials and Methods

2.1. Study Sites

The urban forest sites surveyed during this study were planted as part of the RTB program and represent an annual chronosequence of forest ages planted between 1999 (Cold Stream Park) and 2019 (Masterson Station Park; Figure 1).

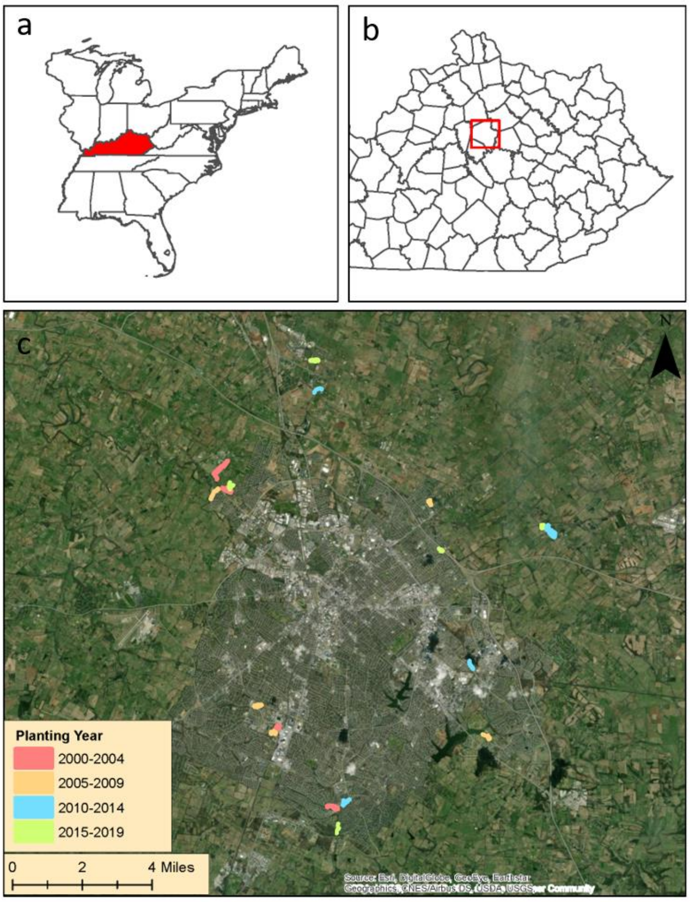

Figure 1. Reforest The Bluegrass planting sites in Lexington, KY, USA. (**a**) The location of Kentucky within the eastern USA; (**b**) the location of Fayette County within the eastern half of KY; (**c**) the distribution of Reforest The Bluegrass sites across the city of Lexington. Sites were planted annually between 2000 and 2019. Figure from Sena et al. (2021).

Because the Cold Stream site was recently disturbed as part of a stream restoration project, this site was excluded from our analysis, yielding 20 total sites representing continuous tree plantings from 2000 to 2019. Prior to planting, all sites were urban grasslands maintained by mowing, nearly all of which are within city parks managed by LFUCG. Planting approaches varied slightly over time. Earlier sites were located primarily in riparian and floodplain areas, and trees were planted in blocks of species based on site preferences: for example, *Taxodium distichum* (L.) Rich. (baldcypress) was planted nearest to streams, but upland *Quercus* spp. were planted in the more upland blocks. However, over time, planted sites expanded to more upland areas, and species were more evenly distributed across sites. All planted trees were native to Kentucky and were nursery-grown 1–0 bare-root seedlings. Trees were planted on 1.2 m × 1.2 m or 1.8 m × 1.8 m spacings, depending on the year. Volunteers planted trees using a tree spade or dibble bar, and weed-barrier mats approximately 1 m^2 were installed around the trees after planting to promote growth and survival.

2.2. Sampling

Permanent vegetation monitoring plots were established in all RTB sites in summer 2020. The number of plots established in each site was generally proportional to site area, but a minimum of 3 plots were established in each site (mean ± SD: 4.6 ± 2.5 plots; max = 9). Plot centers were located at least 19.8 m from one another and from the site edge to avoid edge effects. LFUCG has an active invasive species management program, and patches undergoing invasive species management were avoided to remove biases associated with management. Each monitoring plot featured a nested plot design in which a 0.008-ha circular plot was delineated to survey trees $\geq$ 2.5 cm diameter at breast-height (dbh) and a 0.002-ha circular plot was delineated to survey understory trees and shrubs < 2.5 cm dbh; both plots were concentric on the plot center. Woody plant data are available from Jacobs et al. [39]. To survey the herbaceous understory plant community, a 0.6-m x 0.6-m grid was randomly tossed 10 times within the 0.008-ha plot, avoiding overlapping. All plants present within the grid (excluding woody tree-forming and shrub-forming plants) were identified to the lowest taxonomic level possible according to Jones [40]; the abundance of each species present within a grid was visually estimated as the percent of groundcover in 5% intervals.

Composite soil samples, aggregated from five subsamples of the top 10 cm, were collected within each 0.002-ha plot. Soil samples were analyzed for pH [41], P [42], K, Ca, Mg, Zn [43], texture [44,45], total C [46], and total N (analyzed using a LECO combustion instrument) by the University of Kentucky Regulatory Services Soils Laboratory. The soil sampling and analytical methods, and the results, are described in Sena et al. [47]. Soil data are available from Jacobs et al. [48].

2.3. Statistical Analysis

2.3.1. Chronosequence Diversity Patterns

We calculated a series of alpha and beta diversity metrics to investigate patterns in the development of the understory plant community across the chronosequence of RTB planting sites. To compare diversity metrics among sites, we first performed rarefaction to account for differences in sampling intensity across sites. Rarefaction entailed drawing 10,000 bootstrapped resamples of the intensity of the least-sampled site from target datasets and calculating the metric of interest; the mean of the bootstrapped distribution was used as the rarefied estimate [49–51]. To evaluate temporal trends in alpha diversity, we first calculated rarefied estimates of species richness, the Shannon diversity index, and the Simpson diversity index for each plot; then, we evaluated the relationship of each metric with planting year using non-parametric Spearman rank correlations (ρ) via functions in the *stats* package of the R programming language [52].

To quantify the temporal divergence of herbaceous species assemblages across the range of forest ages, we calculated the pairwise Jaccard Distance between the species observed in the 2000 planting site and those observed in each of the other planting sites. The Jaccard Distance is a measure of beta diversity and quantifies the dissimilarity in species assemblages between two communities, ranging from 0 (i.e., all species are common between the communities) to 1 (i.e., the communities have unique species). To characterize the extent of the relationship between the Jaccard Distance and the planting year, we regressed the Jaccard Distance by planting year using ordinary least squares simple linear regression, executed using functions in the R package *stats*. Year was centered and standardized to have a mean of 0 and standard deviation of 1 prior to modeling [53], and a probit transformation of the Jaccard Distance was performed to satisfy the model's normality assumption. We also fit models with second-degree and third-degree polynomial effects of year and compared all models via Akaike's information criterion, corrected for a small sample size (AIC_c), using functions in the R package *MuMIn* [54] and residual standard error. Since the simple linear regression possessed the lowest AIC_c (year = 13.8, year 2 = 16.9, year 3 = 20.0) and lowest residual standard error (year = 0.3, year 2 = 0.31, year 3 = 0.31), we selected the simple linear regression as our final model. After validating the regression diagnostics of the final model, we evaluated the significance of the yearly effect and the amount of variation in the pairwise Jaccard Distances, controlled by net annual change via the coefficient of determination (R^2).

Since changes in the dominance of plant functional groups are characteristic of forest succession, we analyzed temporal relationships in groundcover dominance among functional groups. We classified observed taxa into one of three functional groups: forbs, graminoids, and vines. Graminoids comprised the families *Cyperaceae* (sedges), *Juncaceae* (rushes), and *Poaceae* (grasses), while woody species with a vining habit were classified as vines. All other non-woody taxa were classified as forbs. Data on woody tree-forming and shrub-forming species were evaluated in Sena et al. [47], and were not collected in groundcover estimates. The groundcover percentage of each functional group was calculated by planting year, visualized, and evaluated for temporal relationships using Spearman rank correlations.

2.3.2. Invasive Plant Species Prevalence

During preliminary site surveys, we found that invasive plant species formed a large component of the understory in many RTB sites. To examine the importance and temporality of invasive species in the understory across the chronosequence, we calculated the percent of groundcover comprised by invasive species within each plot, and evaluated the Spearman rank correlation between planting year and percent invasive species. Further, we examined the influence of invasive species prevalence on local understory diversity. Since the relationship between invasive species prevalence and plant diversity appeared nonlinear, we modeled rarefied estimates of species richness, the Shannon diversity index, and the Simpson diversity index as the response variable in individual generalized additive mixed models, with the percent of invasive species as the explanatory variable using functions in the R package *mgcv* [55]. Planting year was included in all models as a random effect. For each response variable, we fit two models: a model with a linear effect of invasive species prevalence and a model that fit the effect of invasive species prevalence using a penalized cubic regression smoothing spline; smoothing parameters of splines were estimated using a generalized cross validation procedure. We calculated AIC_c to select the better model for each response variable. Models with a spline term for the effect of invasive species prevalence were the better supported models for all diversity metrics. After validating the regression diagnostics of the selected models, we evaluated the significance of the effect of invasive species prevalence on each diversity metric.

2.3.3. Nonmetric Multidimensional Scaling

To investigate the influence of site characteristics on the variation within the understory community, we performed nonmetric multidimensional scaling (NMDS). Importance values (IV) of each taxon were calculated by plot, per the following formula:

$$IV = \left(\frac{\text{Total groundcover of taxon in all grids}}{\text{Total plant groundcover in all grids}} + \frac{\text{Grids where taxon was present}}{10}\right) \times 100$$

Under this formulation, the range of possible IVs per plot is 0 to 200. The mean IV of each taxon was calculated by site to serve as the estimate of site-level importance. Taxa with mean IV < 10 were excluded from the analysis. Bray–Curtis distances were calculated from mean IVs of taxa at each site for use in NMDS. To select an appropriate number of NMDS axes, we performed ordinations with between two and five axes and selected the ordination with the minimum number of axes for which the stress < 0.2. For each ordination, we calculated linear and nonmetric fit statistics (R^2) and visualized the correspondence of the observed dissimilarity and modeled ordination distance using Shepard diagrams. After selecting a final ordination, we calculated Spearman rank correlations to determine the association between continuous site covariates and NMDS axes, and performed a non-parametric analysis of similarities (ANOSIM) with 10,000 permutations, in order to evaluate differences among factor levels of categorical covariates. Site covariates included woody plant community metrics and soil characteristics, summarized in Sena et al. [47], and landscape metrics, including the topographic wetness index and the percent of developed landcover within 1 km of the planting sites (Table 1). Landscape metrics were derived using ArcGIS 10.7 (ESRI, Redlands, CA, USA), the National Elevation Dataset, and the 2019 National Land Cover Database (products courtesy of U.S. Geological Survey). Covariates demonstrating significant non-zero correlations with NMDS axes (continuous) or separation among factor levels (categorical) were considered important drivers of dissimilarity in understory community structure among sites. After selecting a subset of site covariates, we fit the continuous site covariates to the ordination to analyze linear relationships between covariates and NDMS axes. All analyses pertaining to NMDS were performed using functions in the R package *vegan* [56]. All statistical tests were performed at $\alpha = 0.05$.

Table 1. Descriptions and summary statistics of site covariates in Reforest The Bluegrass sites planted annually between 2000 and 2019 in Lexington, KY, USA. Methods describing the collection and analyses of these data are available in Sena et al. [47].

Covariate	Description (Units)	Mean ± SE (Extrema)
Basal Area	Basal area of plantation (m^2 ha^{-1})	9.4 ± 0.9 (0, 39.9)
Carbon	Soil carbon concentration (%)	3.5 ± 0.1 (1.4, 6.7)
Calcium	Soil calcium concentration (mg kg^{-1})	3126.9 ± 127.1 (918.5, 7024.0)
Canopy	Presence of open or closed canopy (Sena·et al., 2021)	-
Clay	Soil clay content (%)	15.0 ± 0.4 (0.6, 30.5)
Developed	Developed landcover within 1 km (%)	59.7 ± 0.03 (3.7, 98.6)
Magnesium	Soil magnesium concentration (mg kg^{-1})	213.0 ± 6.9 (69.0, 497.5)
Nitrogen	Soil nitrogen concentration (%)	0.3 ± 0.01 (0.1, 0.6)
pH	Soil pH	5.6 ± 0.1 (4.0, 7.1)
Phosphorus	Soil phosphorus concentration (mg kg^{-1})	161.8 ± 8.0 (16.5, 400.0)
Potassium	Soil potassium concentration (mg kg^{-1})	149.3 ± 7.5 (42.5, 353.0)
Sand	Soil sand content (%)	16.4 ± 0.4 (9.0, 33.6)
Silt	Soil silt content (%)	68.6 ± 0.6 (41.0, 80.0)
TWI	Topographic wetness index	6.1 ± 0.02 (5.6, 6.7)
Woody Density	Density of woody stems with tree/shrub architecture (stems ha^{-1})	3928 ± 3812 (0, 17,297)
Woody Height	Height of woody stems with tree/shrub architecture (cm)	98.8 ± 6.1 (0, 285)
Year	Year of tree planting	(2000, 2019)
Zinc	Soil zinc concentration (mg kg^{-1})	6.2 ± 1.1 (1.1, 102.5)

3. Results

Across RTB sites planted between 2000 and 2019, we identified understory plants comprising 107 species, 92 genera, and 34 families. *Euonymus fortunei*, a non-native invasive species, was the most encountered species, accounting for 13% of total sampled groundcover across all sites. *Festuca* spp. (fescue)and *Poa pratensis* L. (Kentucky bluegrass) were the second and third most encountered species, representing 7% and 6% of groundcover, respectively.

3.1. Chronosequence Diversity Patterns

Among all sites, species richness was 14.9 ± 0.6 species (mean ± SE), and the mean Shannon and Simpson diversity indices were 1.86 ± 0.06 and 0.25 ± 0.02, respectively. Spearman rank correlations of planting year with rarefied species richness ($\rho = -0.04$, $p = 0.67$), Shannon diversity index ($\rho = -0.04$, $p = 0.68$), and Simpson diversity index ($\rho = 0.04$, $p = 0.68$) indicated no evidence of temporal patterning in understory alpha diversity in RTB sites (Figure 2). Although alpha diversity was similar among sites, the diversity of the 2008 planting site was marginally lower than that of other sites, as evidenced by a lower mean Shannon index and higher mean Simpson index; this reduction in diversity resulted from the dominance of *Euonymus fortunei* in the understory of this site.

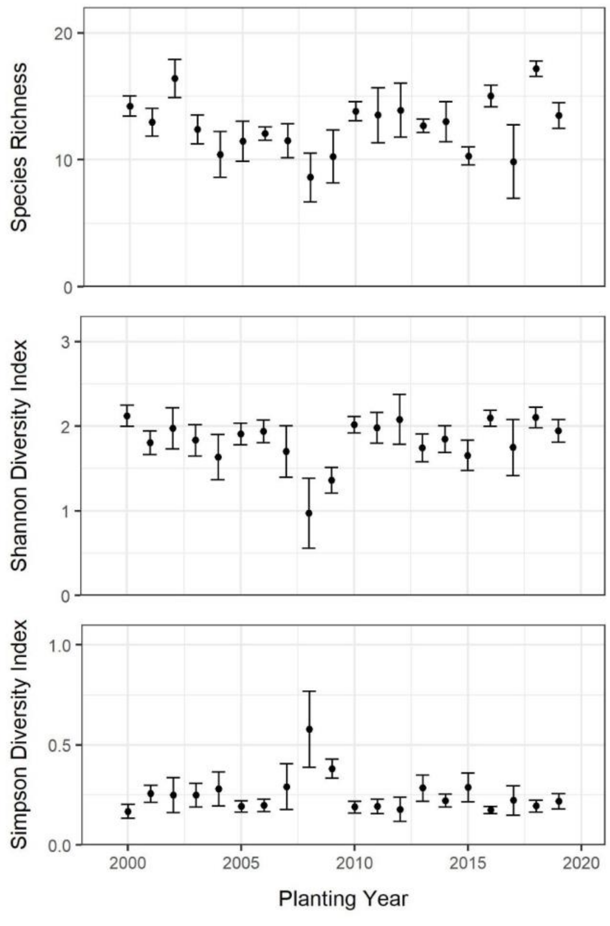

Figure 2. Rarefied estimates (mean ± 95% CI) of species richness, the Shannon diversity index, and the Simpson diversity index of understory plant communities along the 20-year chronosequence of Reforest The Bluegrass plantings in Lexington, KY, USA.

Conversely, a positive effect of planting year was apparent in the pairwise Jaccard Distance between the community assemblages in 2000 and those in successively younger planting sites ($\beta_{Year} = 0.25$, $p = 0.003$; Figure 3). This indicates that understory community composition is increasingly dissimilar, with an annual change in plantation age. The effect of planting year accounted for nearly half of the variability in the pairwise Jaccard Distance of understory assemblages ($R^2 = 0.42$). The mean Jaccard Distance between the assemblages of sites planted in 2000 and 2019 approached 0.9, identifying a near-complete disjunction of species compositions between the sites; the maximum observed pairwise Jaccard Distance was 0.96 with the 2016 planting site. Notably, the assemblages between the sites planted in 2000 and 2001 possessed a Jaccard Distance of 0.62, indicating only a 38% overlap in understory species between the two oldest planting sites.

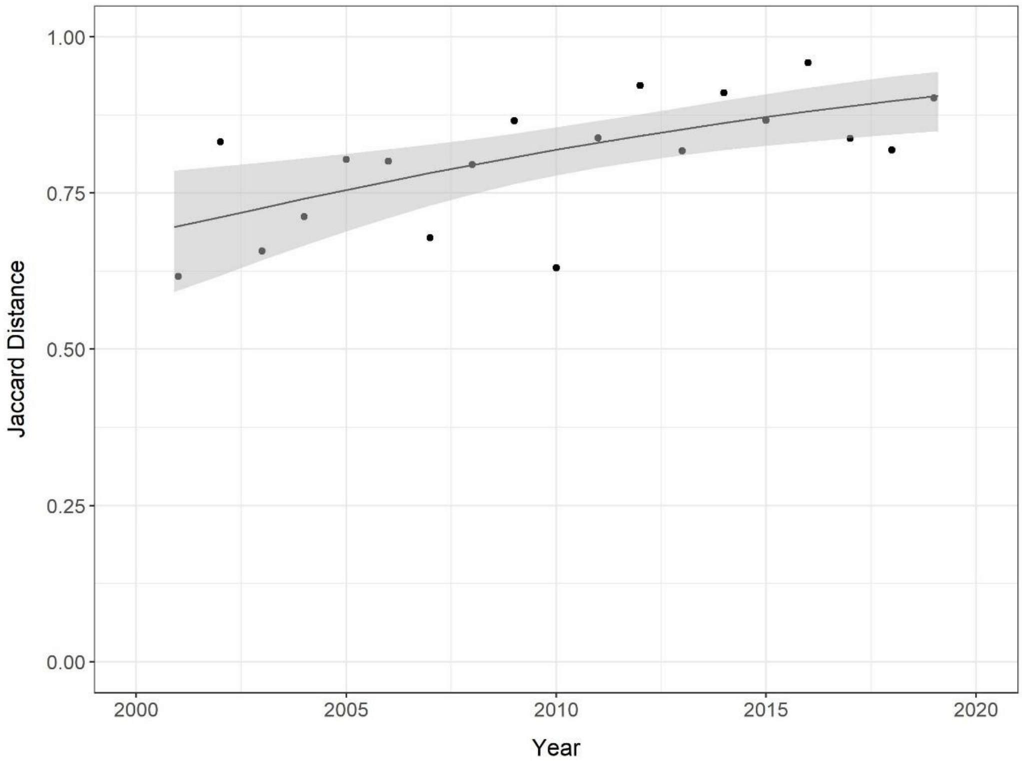

Figure 3. Effect of planting year (regression mean ± 95% CI) on the Jaccard Distance between understory plant assemblages in the Reforest The Bluegrass site planted in 2000 (i.e., the oldest site) and in other planting sites. When the Jaccard Distance = 0, community assemblages are identical, while a Jaccard Distance = 1 indicates complete separation between the communities.

The relative composition of plant functional groups in RTB sites varied significantly with time. Graminoids were positively correlated with planting year ($\rho = 0.73$, $p < 0.001$), possessing the greatest percentage of groundcover in recent planting sites (Figure 4). Among the graminoids, the relative composition of *Poaceae* increased with planting year, while *Cyperaceae* was more abundant in older plantings; *Juncaceae* occurred in only three plots across two sites (2002 and 2018) and represented less than 5% of groundcover in these plots (Figure 4). In contrast to graminoids, forbs ($\rho = -0.46$, $p = 0.04$) and vines were negatively correlated with year ($\rho = -0.6$, $p = 0.006$; Figure 4), indicating an increased prevalence of both groups in older plantings. Species characterizing woody vines included *Campsis radicans* (L.) Seem. ex Bureau (trumpet vine), *Euonymus fortunei*, *Lonicera japonica* Thunb. (Japanese honeysuckle), *Parthenocissus quinquefolia* (L.) Planch.(Virginia creeper), *Toxicodendron radicans* (L.) Kuntze (poison ivy), and *Vitis* spp., although *Euonymus fortunei* comprised 87% of the group's coverage across all sites.

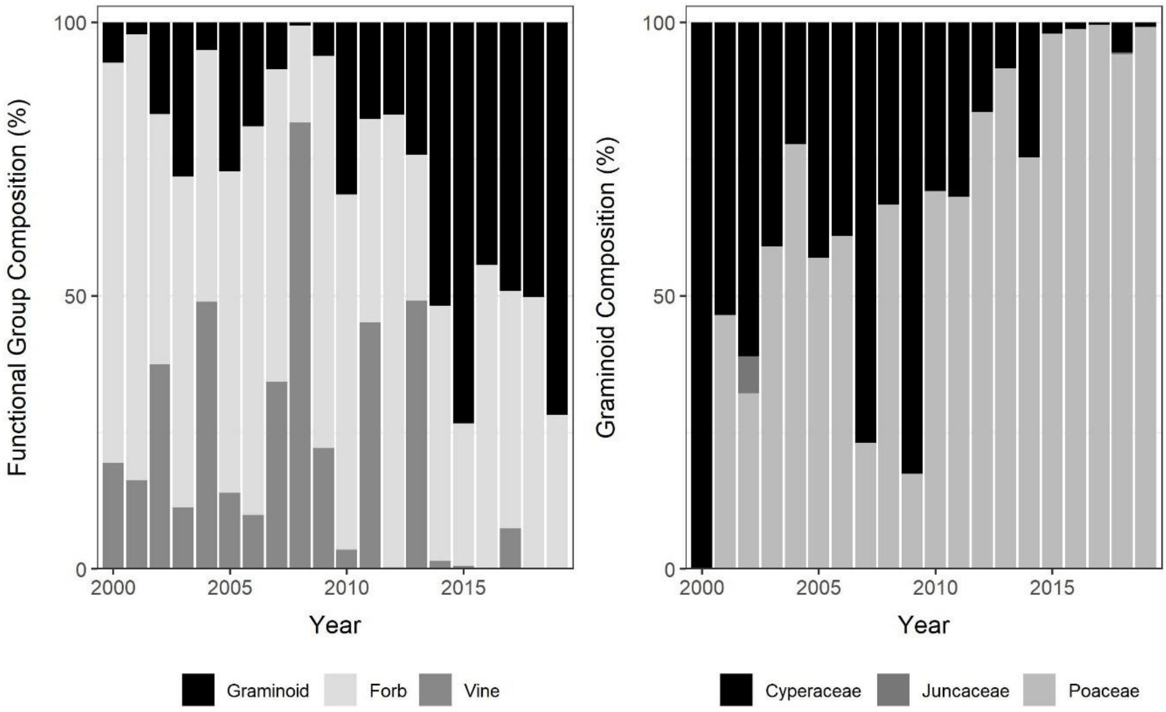

Figure 4. Composition (%) of plant functional groups and graminoids by family along the 20-year chronosequence of Reforest The Bluegrass plantings in Lexington, KY, USA.

3.2. Invasive Species Prevalence

We identified six non-native invasive species occupying understory communities in RTB sites: *Alliaria petiolata*, *Euonymus fortunei, Lespedeza cuneata* (Dum. Cours.) G. Don (sericea lespedeza), *Lonicera japonica*, *Microstegium vimineum* (Trin.) A. Camus (Japanese stiltgrass), and *Sorghum halepense* (L.) Pers (Johnsongrass). These species accounted for 21% of total groundcover across all sites. *Euonymus fortune* and *Alliaria petiolata* comprised 68% and 27% of the invasive component, respectively. The importance of invasive species in the understory decreased with planting year ($\rho = -0.56$, $p < 0.001$), and increased markedly at the onset of canopy closure (2013; Figure 5). Between 2000 and 2013, understory composition of invasive species generally ranged from 25% to 50%. The species importance varied across the chronosequence, according to shade tolerance: *Sorghum halepense* was most abundant in years $\geq$ 2016, but was replaced in older plantings largely by *Alliaria petiolata* and *Euonymus fortunei*.

Generalized additive mixed models identified a significant nonlinear effect of invasive species prevalence on species richness, the Shannon diversity index, and the Simpson diversity index (Table 2). Invasive species prevalence comprised more than 50% of the variability in the Shannon and Simpson diversity indices (Table 2). All metrics indicated a general reduction in alpha diversity in the understory community, with an increased prevalence of invasive species (Figure 6). Diversity was highest when invasive species comprised <~25% of groundcover, remaining largely stable over this interval; however, diversity declined rapidly with a greater prevalence of invasive species.

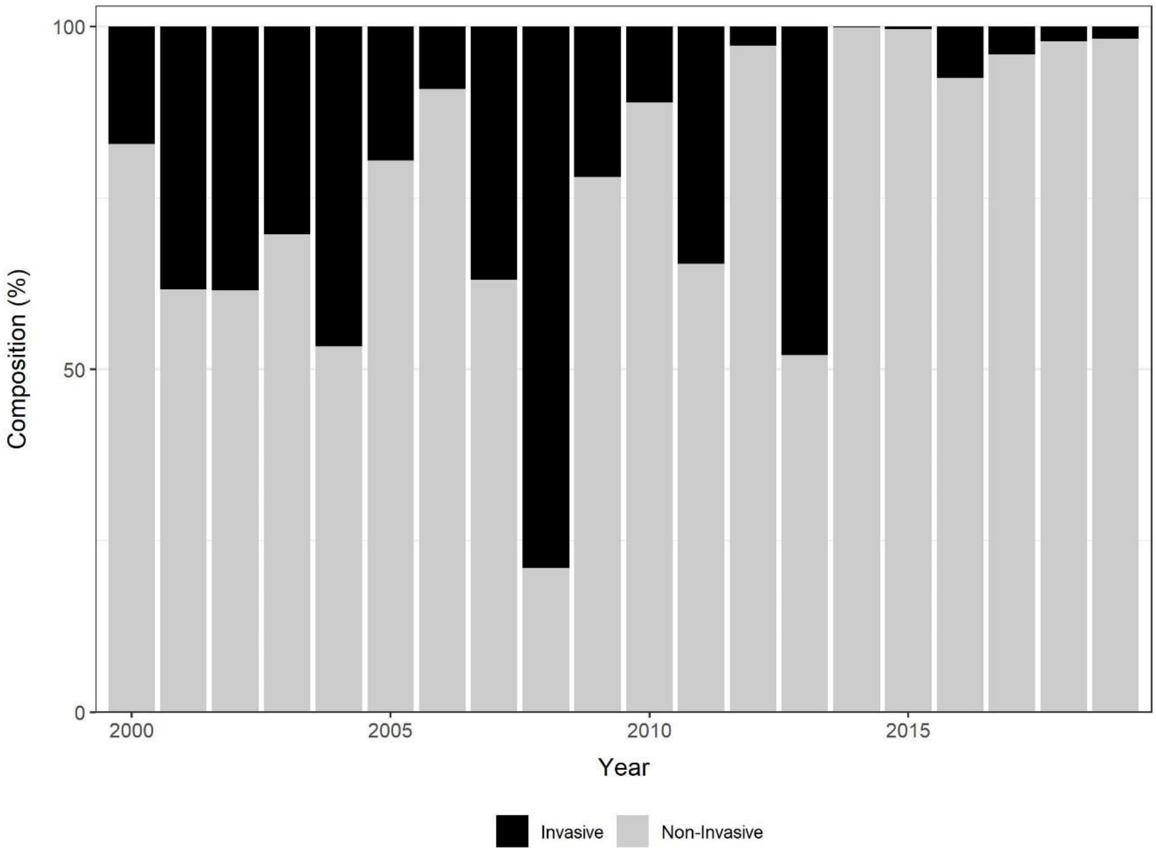

Figure 5. Composition (%) of non-native invasive species along the 20-year chronosequence of Reforest The Bluegrass plantings in Lexington, KY, USA.

Table 2. Fit statistics of generalized additive mixed models with alpha diversity metrics as the response variable and a smoothing spline effect of percent groundcover occupied by invasive species in Reforest the Bluegrass planting sites in Lexington, KY, USA. EDF = effective degrees of freedom of the smoothing spline; F = F test statistic used in an approximate hypothesis test for the significance of the effect of invasive species component, and p = p-value of F test; R^2 is the coefficient of determination.

Response Variable	EDF	F	p	R^2
Species Richness	2.6	16.9	<0.001	0.22
Shannon Diversity Index	3.4	31.9	<0.001	0.52
Simpson Diversity Index	3.5	41.6	<0.001	0.6

3.3. NMDS

After performing NMDS ordinations with 2–7 axes, the ordination with two axes presented an acceptable stress value (0.14) and fit (linear R^2 = 0.91, nonmetric R^2 = 0.98); we evaluated this ordination for relationships with site covariates (Figure 7). Understory communities diverged significantly between sites with open and closed forest canopy (ANOSIM R = 0.85, p < 0.001). Significant non-zero Spearman correlations were found between NMDS axes and four site covariates: planting year (ρ = 0.75, p < 0.001), overstory basal area (ρ = −0.65, p = 0.002), and understory woody plant density (ρ = −0.64, p = 0.002) were correlated with axis 1, while soil pH (ρ = 0.52, p = 0.02) was correlated with axis 2 (Table 3). Fitting vectors for these covariates to the ordination revealed that these effects were linear (Table 4). The effects of planting year and overstory basal area identified the same site-level effect, evidenced by the near-opposite orientations of their respective vectors (Figure 7). An examination of the selected species on the ordination plot identified patterns in group divergence. Grassland species, such as *Asclepias syriaca* L. (common milkweed), *Festuca* spp., *Solidago canadensis* L. (goldenrod), and *Sorghum halepense* were indicative of new plantings with little to no accumulation of overstory basal area. Brambles (*Rubus* spp.) characterized sites transitioning between open and closed canopy, possessing high woody tree densities in the understory, while species occupying forests, such as *Geum virginianum* L. (cream-colored avens) and *Parthenocissus quinquefolia*, were indicative of older planting sites (Figure 7). Three prevalent invasive species—*Alliaria petiolata*, *Lonicera japonica*, and *Euonymus fortunei*—were found typically in closed canopy sites, with relatively high basal areas and low to moderate understory woody densities.

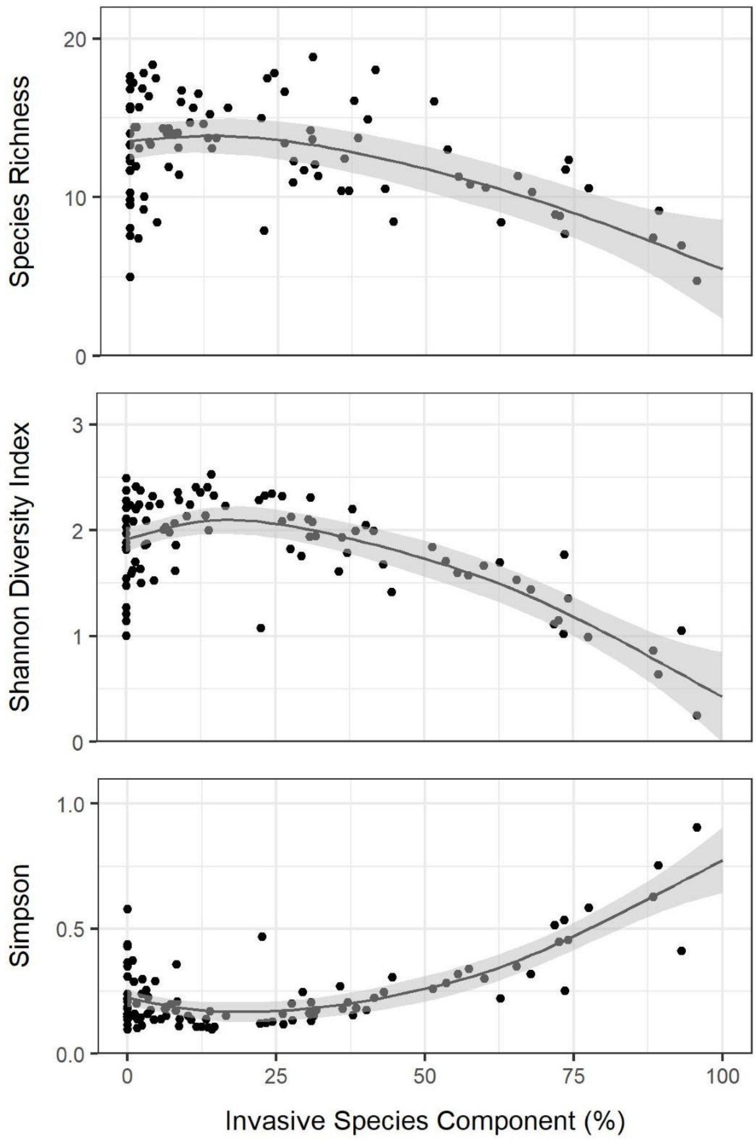

Figure 6. Nonlinear effect (regression mean ± 95% CI) of invasive species prevalence on species richness, Shannon diversity index, and Simpson diversity index of understory plant communities within Reforest The Bluegrass planting sites in Lexington, KY, USA.

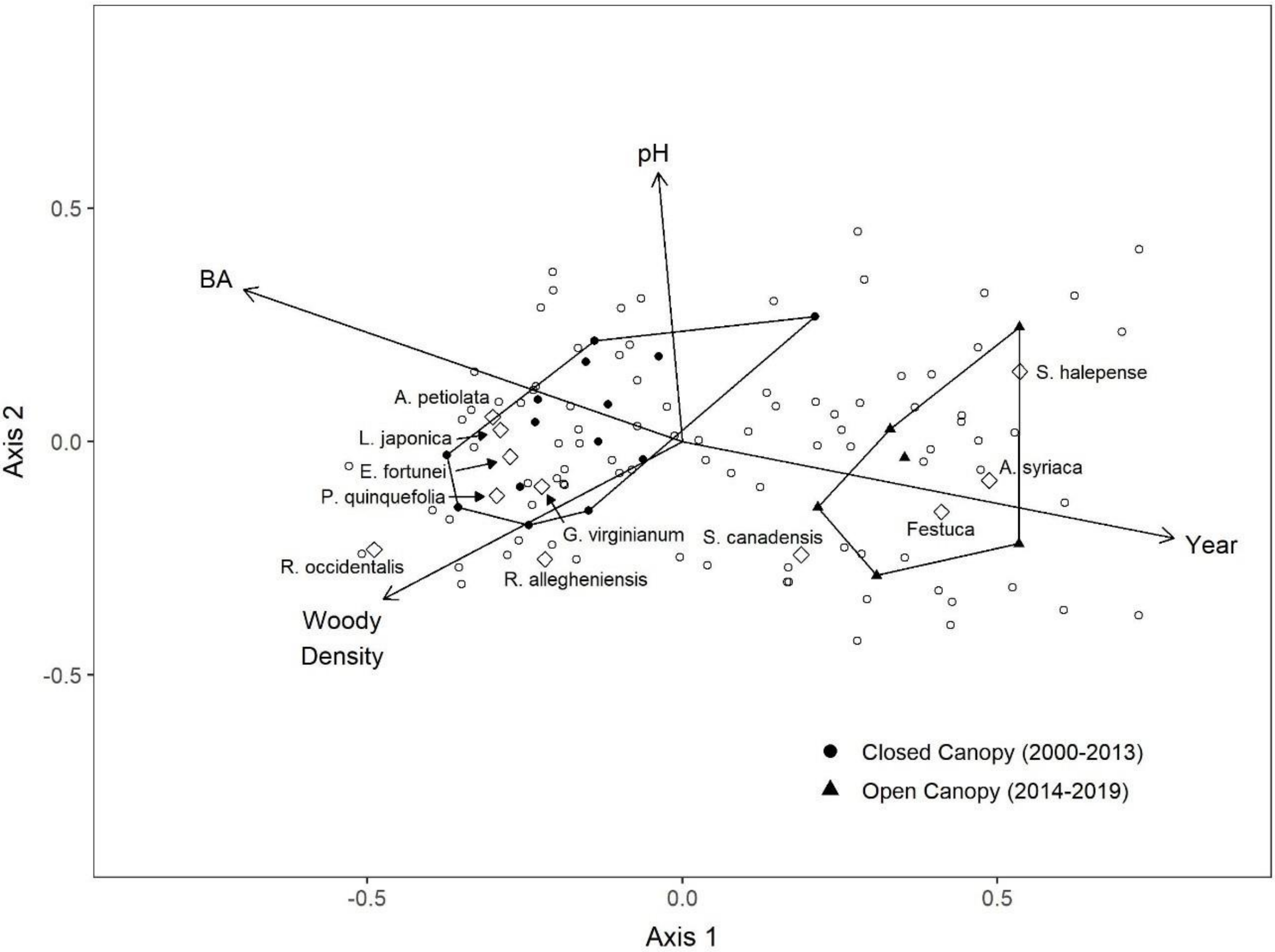

Figure 7. Ordination via nonmetric multidimensional scaling (NMDS) of mean importance values of understory taxa in Reforest The Bluegrass planting sites in Lexington, KY, USA. Open circles (○) identify observed taxa. Important taxa are illustrated with an open diamond (◇) and labeled. Convex hull polygons distinguish clusters of sites with open and closed forest canopy. Continuous covariates with significant associations to NMDS axes are depicted as vectors. A. petiolata = *Alliaria petiolata*; A. syriaca = *Asclepias syriaca*; E. fortunei = *Euonymus fortunei*; Festuca = *Festuca* spp.; G. virginianum = *Geum virginianum*; L. japonica = *Lonicera japonica*; R. allegheniensis = *Rubus allegheniensis*; R. occidentalis = *Rubus occidentalis*; S. canadensis = *Solidago canadensis*; S. halepense = *Sorghum halepense*; P. quinquefolia = *Parthenocissus quinquefolia*.

Table 3. Spearman rank correlations (*p*-value) between NMDS axes and site covariates in Reforest The Bluegrass sites planted between 2000 and 2019 in Lexington, KY, USA. Correlations significantly different from 0 are in bold.

Covariate	Axis 1	Axis 2
Basal Area	**−0.65 (0.002)**	0.21 (0.37)
Carbon	0.1 (0.69)	−0.16 (0.5)
Calcium	0.09 (0.71)	0.36 (0.12)
Clay	0.21 (0.37)	0.04 (0.87)
Developed	−0.24 (0.3)	0.22 (0.34)
Magnesium	−0.07 (0.76)	−0.28 (0.23)

Table 3. *Cont.*

Covariate	Axis 1	Axis 2
Nitrogen	0.09 (0.7)	−0.17 (0.47)
pH	0.08 (0.72)	**0.52 (0.02)**
Phosphorus	−0.1 (0.68)	0.03 (0.89)
Potassium	−0.14 (0.57)	−0.24 (0.31)
Sand	0.34 (0.15)	0.18 (0.44)
Silt	−0.2 (0.39)	−0.11 (0.63)
TWI	0.36 (0.12)	−0.13 (0.59)
Woody Density	**−0.64 (0.002)**	−0.18 (0.45)
Woody Height	−0.21 (0.37)	0.04 (0.62)
Year	**0.75 (0.0002)**	−0.12 (0.62)
Zinc	−0.3 (0.19)	0.39 (0.09)

Table 4. Vectors and linear fit statistics of significant continuous site covariates ($p < 0.05$), with axes from nonmetric multidimensional scaling (NMDS) of mean importance values of herbaceous taxa in Reforest The Bluegrass planting areas, Lexington, KY, USA.

Covariate	Axis 1	Axis 2	p	R^2
Basal Area	−0.906	0.423	<0.001	0.591
pH	−0.066	0.998	0.033	0.333
Planting Year	0.967	−0.256	<0.001	0.652
Understory Density	−0.814	−0.580	0.029	0.339

4. Discussion

Although alpha diversity of the understory community was similar among planting years, temporal shifts in community composition were apparent: recently planted sites were dominated by graminoids, but forbs and vines became more important with increased time since planting. These shifts in understory herbaceous plant communities followed anticipated successional trajectories, from dominance by shade-intolerant to shade-tolerant species, as reported in studies of forest regeneration from clearcuts or old fields [27,57] or in the reforestation of other disturbed landscapes [58]. Templeton et al. [59] reported higher rates of herbaceous species turnover in urban forests than rural forests, which they attributed to interactions between deer browse and high intensities of forest fragmentation. However, the herb layer in planted urban forests has not yet been well documented in the literature: for example, Doroski et al. [60] studied a planted forest in New York City but focused on woody plant recruitment, rather than herbaceous species. Our study provides the first documentation of shifts in herbaceous plant communities, corresponding to secondary succession in planted urban forests. Ongoing monitoring will be necessary to characterize how these communities continue to develop over time, especially as the tree and shrub layers continue to develop.

Invasive species were abundant in RTB sites, comprising 21% of total groundcover. These findings are consistent with the literature, which generally reports significant invasive species pressure in urban and peri-urban forests [17,61,62]. The most common invasive plants in the herb layer of our sites were *Euonymus fortunei* and *Alliaria petiolata*, which are common in forests across the region and are known to negatively affect natural regeneration and recruitment [36,37,63]. Importantly, these problematic invasive species tended to increase in importance in our sites after canopy closure, a critical time period for colonization of native shade-tolerant species. Furthermore, the alpha diversity of understory plants declined as invasive species prevalence increased, suggesting that invasive species may be suppressing recruitment or otherwise reducing colonization and establishment success on these sites. The removal of invasive species, coupled with replacement plantings, can support the recovery of diverse understory plant communities [36,64–66]. LFUCG began removing *Lonicera maackii* and *Pyrus calleryana* from select RTB sites in 2017 (Nathaniel

Skinner, personal communication). While we avoided sampling patches undergoing invasive species management for this study, future work should stratify sampling by invasive species management activities to evaluate how management influences forest development over time. In addition, our results suggest that management targeting *Euonymus fortunei* and *Alliaria petiolata* in addition to problematic tree and shrub species is essential. Ongoing monitoring will be necessary to evaluate the role of continued invasive species management on both herbaceous and woody plant communities within these sites.

NMDS showed a clear separation between understory herbaceous plant communities in open-canopy and closed-canopy sites. This separation aligns with the observed community shifts from dominance by graminoids to dominance by forbs over time since planting. Furthermore, NMDS identified the soil pH as a key site factor, structuring plant communities across these sites. Soil pH is a critical determinant of plant nutrient availability and can exert a profound influence on plant community structure and composition, especially in the restoration of degraded lands [67]. Urban soils are highly heterogeneous and exhibit complex effects of prior management [68]; these, and other legacy effects of human activity, structure plant communities [69,70]. This study documents soil pH as a key determinant of understory plant community structure in planted urban forest sites. The ongoing management of planted sites, as well as selection and planning for planting future sites, should consider soil pH and other soil chemical characteristics to ensure that planted species are tolerant of the soil conditions.

Overall, this study documents herbaceous plant community development in planted urban forests across a chronosequence of ages, between 1 and 20 years. Interestingly, these sites developed successionally, as would be expected in a naturally regenerating forest in this region. Herbaceous plant communities were structured by forest overstory development (i.e., formation of a closed canopy and associated shading of the understory), as well as by the abundance of invasive species and soil chemical characteristics. These factors further demonstrate the importance of canopy closure, invasive species, and edaphic conditions in regulating the dynamics of understory herbaceous plant communities; they further underline the critical role of management in structuring ongoing planted forest development. Continued research on these sites will be necessary to understand how plant communities develop into the future, especially as influenced by management activities, such as the removal of *Lonicera maackii* or *Pyrus calleryana*. With careful planning and coordination, management on these sites can be structured in a way to support a more experimental, rather than observational, study in the future.

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

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Influence of the Urban Green Spaces of Seville (Spain) on Housing Prices through the Hedonic Assessment Methodology and Geospatial Analysis

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Abstract: The city of Seville (Spain) is made up of a historical network of pre-existing city overlaps, which increase the economic and heritage value of certain urban areas. To date, green spaces are one of the most important variables in determining the economic value of housing. Thus, this paper uses the hedonic technique and geostatistical analysis with GIS as a methodological approach to infer the economic influence of urban green spaces on housing prices. Along with the traditional variables used to explain dwelling prices, the size of the green space has also been taken into account as an environmental variable affecting prices. The sample consists of 1000 observations collected from Seville. According to the findings, the most relevant variables depend on the hedonic model. Still, in general terms, a dwelling's selling price is related to basic explanatory variables such as living area, number of rooms, age, and number of baths. The green area per inhabitant present in a dwelling's district is also included as part of these basic explanatory variables. In conclusion, the hedonic linear model is the model that best fits housing prices where the values are similar to those obtained by kriging regardless of the district. Based on this research, each square meter of green space per inhabitant in a district raises the housing value by 120.19 €/m^2.

Keywords: hedonic method; GIS; geospatial analysis; urban green space; housing prices

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1. Introduction

Green spaces serve essential environmental and recreational functions [1]. Forest and urban vegetation, in edaphoclimatic terms, improve the environment in which they are found and serve as the foundation for the conservation of fauna and flora. Recreational activities with a basis in nature are becoming more popular and, while the effects are on a smaller scale, urban parks serve the same environmental and recreational functions as larger forests and green spaces.

Gardens and city parks play the primary environmental function of absorbing carbon dioxide (CO_2) emissions. These emissions are primarily generated through the use of private vehicles in urban transportation. Moreover, emissions have increased significantly in recent decades. It is worth noting that, in Spain, each person in a large city emits 4.62 tonnes of CO_2 per year [2]. Given that one hectare of Mediterranean forest can absorb approximately four tonnes of CO^2 per year, a simple calculation leads us to conclude that we require more than one hectare of green space per inhabitant (inh) to offset the pollution generated by these emissions. The preservation of urban green spaces is thereby becoming increasingly important in order to combat the growing contamination of our cities.

Additional factors, such as acoustic isolation, should be included in the list of the environmental functions of urban green parks as some gardens serve as acoustic screens between high-traffic roads and residential areas. Plants have individual and collective aesthetic value which contributes significantly to preserving a pleasant landscape in addition to serving as a link between residential, urban, and industrial areas. Many recreational activities (including children's play areas, landscape enjoyment, and sports) take place in city parks and gardens. The abundance of services provided by urban green spaces help to explain the impact of environmental variables on housing prices.

However, the benefits that vegetation brings to the urban environment have no (direct) economic value because they are intangible goods [3]. Subsequently, their economic valuation is a complex and time-consuming task. The difficulty of applying monetary value prevents these open spaces from being adequately accounted for in cost-benefit analyses of public urban planning policies. As a result, we risk seeing urban green space endowments fall below the social optimum.

Economic science has developed specific methods for capturing the monetary value of environmental assets. This value is sometimes indirectly determined by observing people's behaviour as in the travel cost method (TCM). Other methods, such as contingent valuation (CVM), determine an environmental asset's value by asking people how much they are willing to pay for its use or conservation. This final method is highly versatile and has been used to value different projects such as the valuation of mining heritage in Extremadura (Spain) [4], the assessment of landowner demand for forest amenities in Andalusia (Spain) [5], as well as the social and private costs of water for irrigation in San Vicente del Raspeig, (Spain) [6].

As has been proven in different recent studies, Geographic Information Systems (GIS) can help improve the understanding of urban green spaces worldwide (i.e., Africa [7], Europe [8–10], Asia [11], America [12,13], or Oceania [14]).

The hedonic pricing method (HPM) is another model for assessing the monetary value of an environmental asset [15–17]. In this method the value is obtained indirectly through the environment's influence on the market price of another good. Similarly, the value of a particular dwelling can be inferred through geostatistical analysis of existing prices in the study area using a GIS. This paper uses these methodologies to assess the influence of urban green spaces on housing prices in the Andalusian capital, Seville (Spain) since it is a pioneer in urban sustainability [18]. The novelty of this research is conferred by the fact that a study of these characteristics had never before been undertaken in this city. A representative sample of this city's current real estate market was chosen. The data set includes the sale price and other key characteristics for 1000 residential dwellings. Traditional housing price determinants (i.e., size, number of rooms, and age) were considered, and the relative sizes of green areas were also considered as an environmental factor.

The rest of this manuscript is structured as follows: Section 2 defines the fundamentals with regard to the hedonic pricing method and the empirical models used in dwelling valuation; in Section 3 the study area is introduced; Section 4 deals with the materials and methods; Section 5 presents the results and discusses them; and finally, Section 6 outlines the conclusions of the research.

2. Fundamentals

2.1. Hedonic Pricing Method (HPM)

According to Glumac et al. [19], some references specify that the origins of HPM may extend prior to the 1970s. Generally, the hedonic pricing method connects a good's market price to its characteristics. Thus, the monetary value of each characteristic can be calculated by observing the differences between the market prices of commodities with the same attributes. The initial hypothesis asserts that goods are made up of a diverse set of attributes or characteristics. As a consequence, when we engage with a good or service we can consider the price we might pay for it to be the sum of the prices we would pay for each of its characteristics; therefore, it can be inferred that an implicit price exists for each of the attributes that define the whole good or service. For this reason, the price can be expressed as (Equation (1)):

$$P = f(x_i)\ ; i = 1, \ldots, n \tag{1}$$

where "P" denotes the market price of the good and "x_i (i = 1, . . . , n)" indicates the characteristics it possesses. The partial derivatives of the price, with respect to the preceding variables [$\delta(P)/\delta(x_i)$], provide information on the marginal willingness to pay for an additional unit of each characteristic; thus, the implicit price of each of them can be estimated. However, the hedonic theory does not provide a foundation for determining the functional form used. Li et al. [20] suggest linear, semilogarithmic, and double logarithmic forms instead of quadratic forms when some relevant explanatory variables are omitted.

In recent decades, the prices for a wide range of goods have been studied from a hedonic standpoint. The method's most common applications have been in the valuation of environmental externalities in real estate market analysis [21]. Given that housing is a multiattribute good, pricing is determined by a range of variables such as size, age, room number, number of baths, etc. When identical characteristics are shared, environmental factors such as green area surface, among others, may explain differences in market prices. The following is a formula for the price function (Equation (2)):

$$P = f(x_i,\ z); i = 1,\ \ldots,\ n \tag{2}$$

where "P" is the household market price; "x_i (i = 1, . . . , n)" are structural characteristics (e.g., size, age, room number, number of baths), and "z" is the hedonic variable, i.e., environmental variable without a market price.

The method's essence is in ascertaining the portion of the price that can be accounted for by the hedonic variable. These datapoints are obtained by taking the partial derivative of the price concerning the variable "z" [$\delta(P)/\delta(z)$], which gives us the marginal willingness to pay for an additional unit of the environmental asset, and thereby allows us to estimate its monetary value.

Many studies have been conducted using the hedonic approach to determine the relative value of environmental externalities [22] caused by air pollution and traffic, among other variables. For example, Lu [23] uses a data sample that includes 2996 listings in real estate databases; in which, the hedonic technique is applied to value south-facing houses in Shanghai city. Dumm et al. [24] mention more recent works on housing prices related to moral hazards associated with given residential properties. Moreover, Hong et al. [25] apply this methodology to evaluate the random forest approach in South Korean residential properties. Regarding the environmental externalities, Bherwani et al. [26] examined a set of methods used to appraise environmental externalities, and Mei et al. [22] estimated the economic value of domestic water pollution from shale gas.

In terms of urban planning, some modern applications of the method have focused on the analysis of the effects of a shopping mall on housing prices [27], the effect of tourism activity on housing affordability [28], the impact of distance to green areas on property values [29], and air quality [30]. Other aspects that have been investigated include the use of genetic algorithms [31] and automated valuation models [32].

2.2. Empirical Models Used in Dwelling Valuation

As is well known, the relationship between the selling price and the housing characteristics (e.g., living area, number of rooms, age, number of baths) can take several functional forms [15].

If the price relationship linking housing characteristics is assumed to be linear [33], Equation (2) can be written as (Equation (3)):

$$P_i = \sum_{i=1}^{n} \left(b_i \cdot x_{i,j} + b_z \cdot z_j + \varepsilon_j\right); j = 1,\ \ldots,\ T \tag{3}$$

where "$x_{i,j}$, z_j (i = 1,..., n; j = 1,..., T)" are variables describing housing "j"; the parameters "b_i, b_z (i = 1,..., n)" are the marginal willingness to pay for each attribute; "ε_j" is the error term; and "b_z" term is the marginal willingness to pay for an additional unit of the environmental good "z". It is crucial to specify that the willingness to pay for an additional unit remains constant under the linear specification, i.e., it is unaffected by the starting level of "z". This assumption is a significant constraint because, as Rosen points out, there are numerous reasons to believe that the relationship between the price and the environmental variable is nonlinear [34]. As a result, logarithmic specifications are frequently used, though linear models remain popular due to the ease of parameter interpretation.

A logarithmic model, on the other hand, allows us to measure the impact that changes in explanatory variables have on the dependent variable in relative terms [35]. Because the main variable explaining the price is the living area of the housing, the logarithmic model only includes this single variable. If the price equation (Equation (4)) takes the form shown below, where "α" and "β" are parameters, "S" refers to the dwelling's living area, and "u" is the error term. Then the willingness to pay for an additional unit of living area is not constant because "$\delta(P)/\delta(S) \neq \beta$".

$$P = \alpha \cdot S^{\beta} \cdot e^{u} \quad (4)$$

Taking the logarithms in Equation (4), it is possible to obtain Equation (5):

$$\ln(P) = \ln(\alpha) + \beta \cdot \ln(S) + u \quad (5)$$

where "β" is the elasticity of housing size–price according to Equation (6):

$$\beta = \frac{\partial \ln(P)}{\partial \ln(S)} = \frac{\left(\frac{\Delta(P)}{P}\right)}{\left(\frac{\Delta(S)}{S}\right)} \quad (6)$$

In another vein, according to Vásquez Sanijez [36], the formulation of a reciprocal model can provide helpful information on the real estate market. This specification was formulated by leaving "$1/S$" as the single explanatory variable. Equation (7) shows the relationship between the different variables that appear in this model:

$$P = \alpha + \beta \cdot \left(\frac{1}{S}\right) + \varepsilon \quad (7)$$

As can be seen from Equation (7), parameter "α" is the ceiling price at which a dwelling would be sold in this case because as "S" increases, "P" approaches "α". In this equation "ε" is the error term.

3. Study Area

As is well known, the city of Seville is the capital of the Autonomous Community of Andalusia, Spain (Figure 1), and as of January 2021, it comprised 684,234 inhabitants (www.ine.es (accessed on 4 November 2022)). It has been subject to continuous transformation throughout its history, thereby allowing it to adapt systematically to the passage of time while always maintaining the base of the pre-existing city.

Urban development policies in this city have given rise to a process of environmental sustainability focused on maintaining an adequate level of development while not endangering existing natural resources [37].Presently, the existence of a dual relationship between a city's functioning and its ecosystem's sustainability has resulted in a massive diversification of property offers with the added value of green areas positively influencing the final prices houses.

In recent years, the housing price evolution in Seville has had an interannual increase of 6.2% [38]. This fact has led to a slight stagnation in home sales, and therefore, to an increase in properties for sale with less demand. As a result, the average home sales price in Seville is reminiscent of the sales prices in the fourth quarter of 2012 when the economic crisis of 2008–2014 brought about a price decrease of around 10% over 2008 rates. Nevertheless, the current economic situation brought about as a consequence of the war in Ukraine will cause this effect to translate into a progressive increase in the value of housing. This increase is likely to reach its maximum within one to two years.

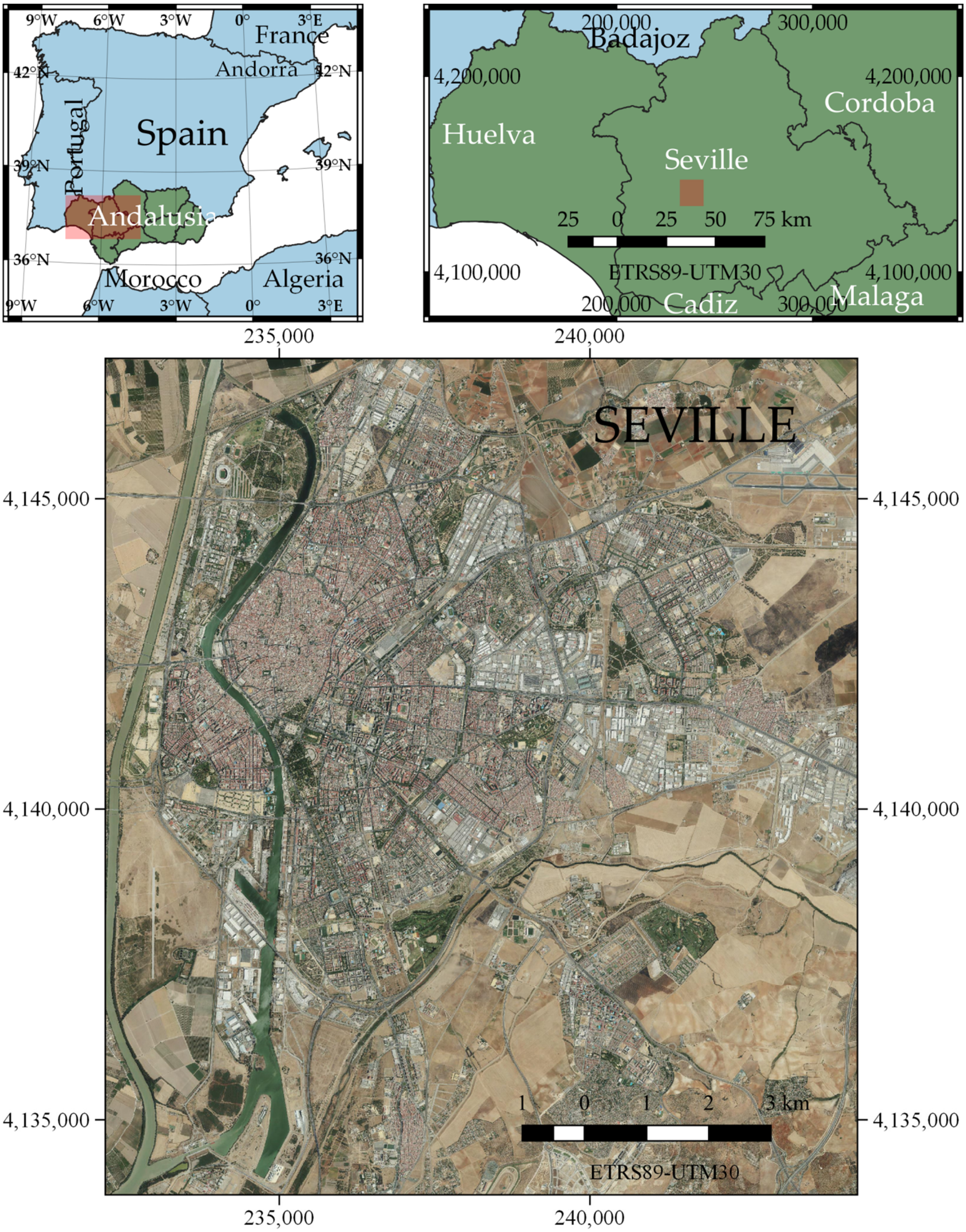

Figure 1. Geographical Seville, Spain context. Source: Own elaboration from www.ign.es (accessed on 5 November 2022) and https://www.juntadeandalucia.es/institutodeestadisticaycartografia/DERA/ (accessed on 5 November 2022).

In the medium term, the consequences can be minimized through a set of local development policies aimed at sustainable development. Additionally, using the housing stock for sale may also have a mitigating effect. Under this course of action, green spaces will have to play an active role if the city government intends to maintain Seville's role as a sustainable urban centre on an international level.

4. Material and Methods

In this research, a total of 1000 observations of housing values in the Seville capital were collected during August of 2022 from Idealista S.A.U (www.idealista.com (accessed on 17 October 2022)). Figure 2 presents the flowchart of this research.

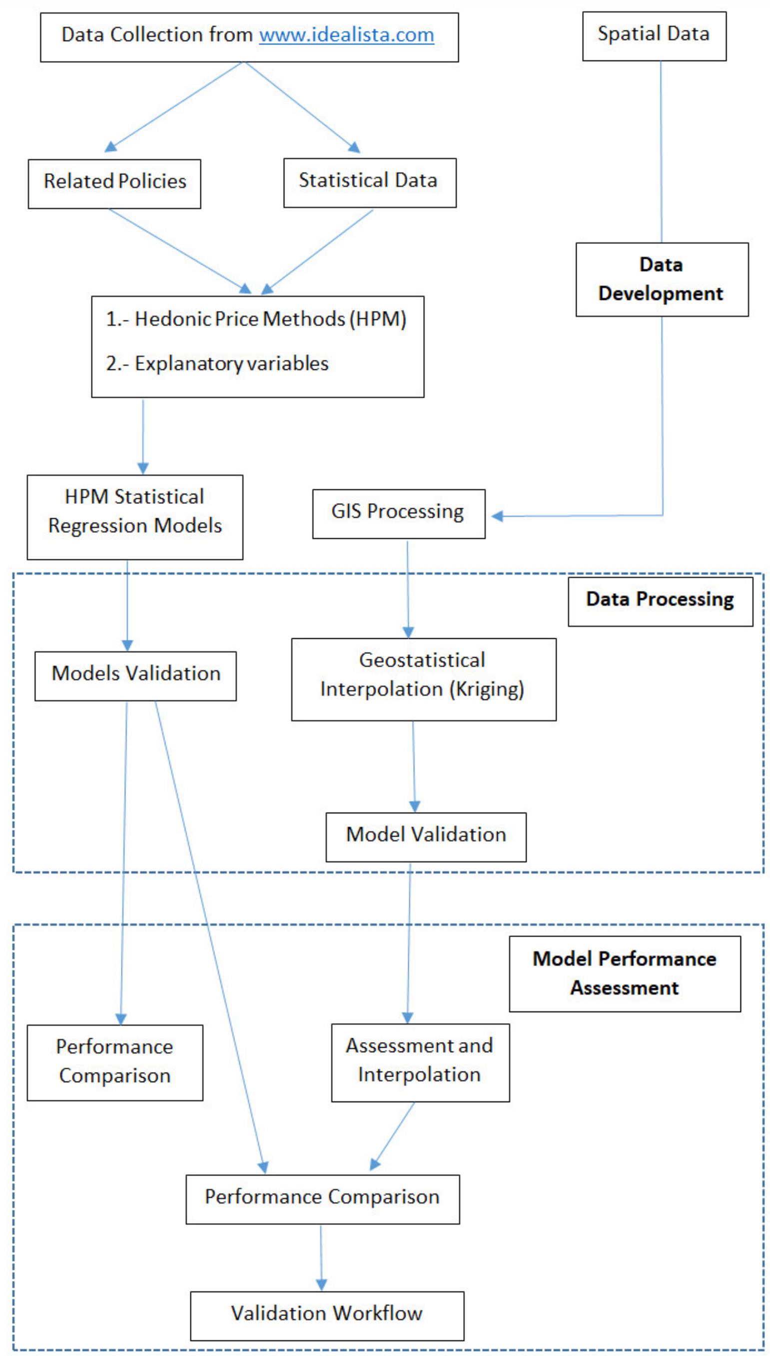

Figure 2. Flowchart of this research. www.idealista.com (accessed on 17 October 2022).

In order to facilitate and organize the data collection correctly, a decision was made to group observations according to zones corresponding to one or more districts of the city. To adequately select the sample "n" that was to be considered in each set of districts (Table 1), it was decided that stratified random sampling should be used (stratified random sampling is a technique used when clearly identifiable subgroups or subpopulations can be distinguished in the population).

Table 1. Data grouping and observations using a set of districts (Own elaboration).

District(s) of Seville Capital	n (Observations)
Triana	73
Torreblanca-Sevilla Este-Parque Alcosa	160
Santa Justa-Miraflores-Cruz Roja-San Pablo-Santa Justa	92
San Jerónimo-Pino Montano	111
Prado de San Sebastián-Felipe II-Bueno Monrreal-La Palmera-Los Bermejales-Bellavista-Jardines de Hércules	107
Nervión	79
Macarena	114
Los Remedios	39
Cerro-Amate	138
Centro	88
Total	1000

In each dwelling for sale the selected independent variables are specified in Table 2.

Table 2. Explanatory variables taken into account (Own elaboration).

Independent Variables	Specification
Size (m^2)	Property area in m^2
Rooms (n°)	Number of bedrooms
Baths (n°)	Number of bathrooms
Age (years)	Dwelling age in years
Green area (m^2/inh)	Green area in the set of districts presented in m^2 per inhabitant
Property sale semester (dummy variable)	This variable will be equal to 1 when the property has been sold in a given period, otherwise its value will be 0

In another vein, Table 3 gives the mean values of the explanatory variables.

Table 3. Mean values of the explanatory variables (Own elaboration).

Variables	Mean Value
Size (m^2)	100
Rooms (n°)	4.2
Baths (n°)	1.8
Age (years)	22.8
Green area (m^2/inh)	17.14

From these explanatory variables the dependent variable (€/m^2) was derived by applying the HPM, which was then compared with values inferred for both the Logarithmic Model (LM) and the Reciprocal Model (RM).

On the other hand, in order to know how a property's situation affects the sale price, a geostatistical interpolation was carried out using a regression of Gaussian processes (Kriging) through an open-source geographic information system QGIS (www.qgis.org (accessed on 21 September 2022)). This was done with the aim of explaining the relationship between dwelling situation and housing price. A District Index (DI) was calculated as the average price per m^2 and was taken into account (Table 4) in accordance with Solano-Sánchez et al. [39]. Under the predefined hypothesis, a higher value per m^2 in a district implies a higher dwelling value. This index was created by assigning one value to the city's most expensive district and then assigning a proportional value to the remaining zones. In order to be able to test and validate this study, a comparison of real price (www.idealista.com) versus estimated price for each HPM model will be conducted.

Table 4. District Index (DI) value for each set of districts (Own elaboration).

Set of Districts	€/m²	DI
Triana	2715.69	0.865
Torreblanca-Sevilla Este-Parque Alcosa	1207.94	0.385
Santa Justa-Miraflores-Cruz Roja-San Pablo-Santa Justa	1919.3	0.612
San Jerónimo-Pino Montano	1188.24	0.379
Prado de San Sebastián-Felipe II-Bueno Monrreal-La Palmera-Los Bermejales-Bellavista-Jardines de Hércules	2497.18	0.796
Nervión	2642.49	0.842
Macarena	1368.73	0.436
Los Remedios	2899.17	0.924
Cerro-Amate	1017.51	0.324
Centro	3137.89	1

Finally, a literature review was conducted to analyze the results obtained in this study and to carry out a coherent discussion concerning the works published to date.

5. Results and Discussion

Following the data analysis, it was discovered that including the green area (m^2/inh) variable in the price equation allowed for the estimation of the influence of environmental factors on dwelling market value. In order to find out if the HPM presents multicollinearity, it was decided that obtaining the Variance Inflation Factor (VIF) (Table 5) would be required. As is well known, if the VIF value for each independent variable is greater than ten then the multicollinearity is considered to be high.

Table 5. Independent variables and coefficients of linear HPM model (r = 0.85, R^2 = 0.721, $p \leq 0.001$) (Own elaboration).

Variables	Coefficients	Stand. Error	Student's t	Prob.	VIF
Constant	−120.443	14.795	−0.075	0.000	-
Size (m^2)	30.032	0.039	1.7	0.000	1.622
Baths (n°)	98.725	0.042	0.14	0.000	1.467
Age (years)	−53.31	1.42	−1.42	0.000	1.535
Green area (m^2/inh)	11.145	0.87	0.872	0.000	1.020

Regarding the HPM model selected as the most satisfactory, it should be mentioned that the linear function form was found to be the most appropriate after performing the data analysis. Like the VIF, Table 4 also displays the independent variables' coefficients.

As for the logarithmic model, in addition to the VIF value, Table 6 provides the differences with respect to the linear model. Thus, the main difference is the dependence on the number of rooms (Rooms) variable in the logarithmic model. In contrast, under the linear model, the property's value depends on the dwelling area (Size) variable. This may be because of the relationship between both variables which causes the predominant variable to cancel the slave variable in the requisite model depending on the selected model.

Table 6. Independent variables and coefficients of the logarithmic HPM model (r = 0.816, R^2 = 0.667, $p \leq 0.001$) (Own elaboration).

Variables	Coefficients	Stand. Error	Student's t	Prob.	VIF
Constant	6.56	1.49	4.36	0.000	-
Room	1.39	1.08	1.29	0.000	1.705
Baths (n°)	0.26	0.6	0.432	0.000	1.523
Age (years)	−0.365	0.205	−1.78	0.000	1.380
Green area (m^2/inh)	−0.013	0.13	−0.1	0.000	1.000

If the reciprocal model is analyzed, Equation (8) is obtained (r = 0.647, R^2 = 0.42, $p \leq 0.05$):

$$P = 5581.151 - 344,864.49 \cdot \left(\frac{1}{S}\right) \quad (8)$$

After the reciprocal model's price estimation (Figure 3) is represented, it can be observed that the price function shape in the limit, "P" trends towards "α = 5581.151". The term "$-(\beta/\alpha)$" refers to the smallest amount of surface available in a dwelling (61.79 m^2 in this study).

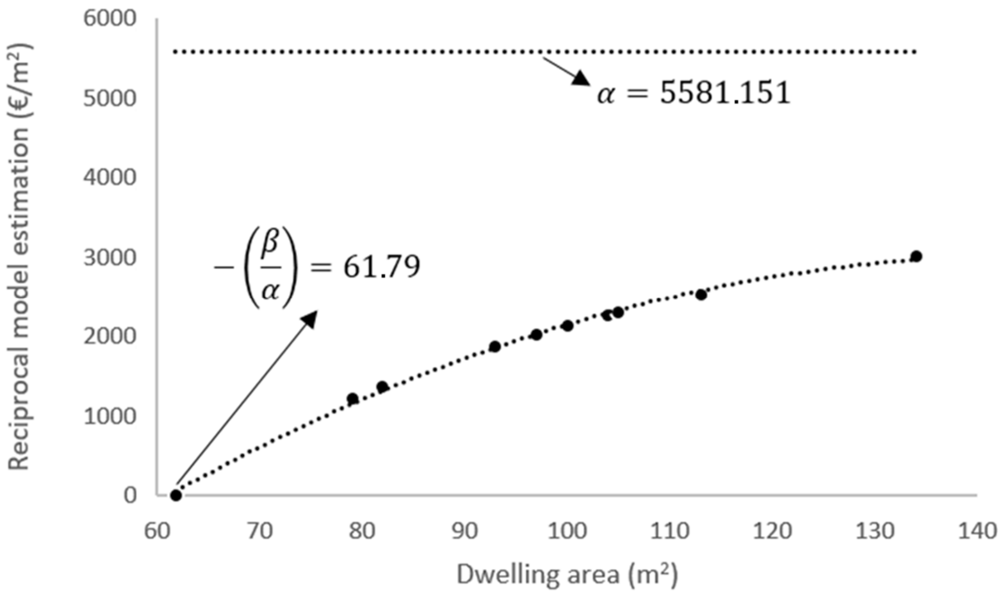

Figure 3. Reciprocal model representation when "$\alpha > 0$" and "$\beta < 0$". (Own elaboration).

If the three models are compared based on the coefficient of determination (R^2), it can be said that a higher value of this coefficient implies a better estimate of the housing price. For this reason, the linear model explains 5.4% more of the predicted price than the logarithmic model and 30.1% more than the reciprocal model. On the other hand, the logarithmic model explains 24.7% more of the estimated price than the reciprocal model.

Additionally, the Chow test [40] was used to ensure the models' stability. It should be noted though that the Chow test has its origin in economics. Nevertheless, it has also been applied to other fields such as renewable energies [41], flood risk assessment [42], and spatiotemporal disease diffusion [43]. In this study, the results revealed that no structural changes occurred exclusively in the parameters of either the linear or logarithmic models. This can be seen in Figure 4, which compares the real price (from www.idealista.com (accessed on 18 October 2022)) to the estimated price for each model used. As can be seen, Figure 4 allows for the simulation of hypotheses that facilitate the validity of the study to be tested.

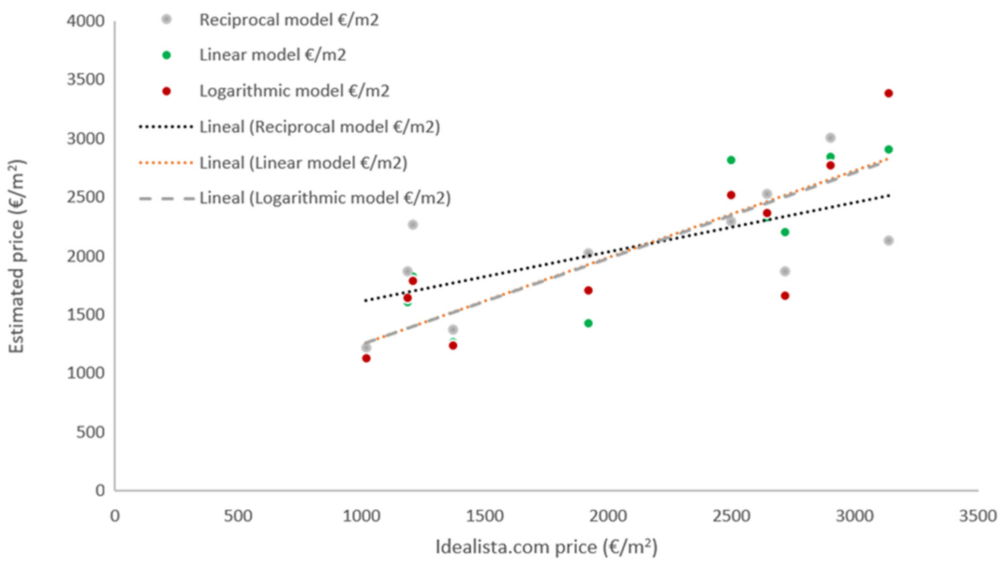

Figure 4. Comparison of real (www.idealista.com (accessed on 17 October 2022)) versus estimated prices for each HPM model. (Own elaboration).

When the models' degree of fit is perfect, they should appear as point clouds in a diagonal line starting at the origin (1017.51; 1119.94 in this study), as shown in Figure 4. In this case, the estimated values for linear and logarithmic models indicate that the linear form is a good fit. However, the reciprocal model presents a trend line that does not coincide with the indicated origin. For this reason, the model does not have as much stability as the linear and logarithmic ones.

Furthermore, with regard to the kriging, Figure 5 shows the geostatistical price interpolation for the city of Seville. As is well known, in order to perform predictions using kriging the forecasting system must be geometrically defined at some point. This means that we must establish the neighbourhood of the data that will intervene in the approximation. It is possible to use all the dwelling prices (assuming a global neighbourhood) and a set of data (considering a local neighbourhood) in the estimation. In practice, only house prices within a predefined circumference or ellipse centred on the estimated point are used. Obviously, the proximity of the data for each point to be valued will differ, thereby necessitating a different kriging equations system for each point on the map at which a prediction is desired. On the other hand, this method allows for the synthetic representation of housing price estimates in the form of a colour map. This representation is generated by performing predictions on the nodes of a regular mesh. In this manuscript the housing price has been estimated at each node of a 10-m-sided regular mesh.

The map in Figure 5 displays how the more valuable areas coincide with those closest to the city centre. The least valued areas, on the other hand, are primarily in the districts of San Jerónimo-Pino Montano, Torreblanca-Sevilla Este-Parque Alcosa, and Cerro-Amate. This is primarily due to a shift in buyer preferences following the COVID-19 pandemic. Following confinement the percentage increase in the preference for housing (new or used) with a balcony was around 80% [44]. As a result, the average percentage decrease in housing prices was 5% across the districts, except for the Centro district which is dominated by homes with small balconies and a communal roof terrace. In order to compare the kriging values in terms of €/m^2 with those of the analyzed models, Table 7 lists the average values per district corresponding to the centroid established in the geospatial analysis.

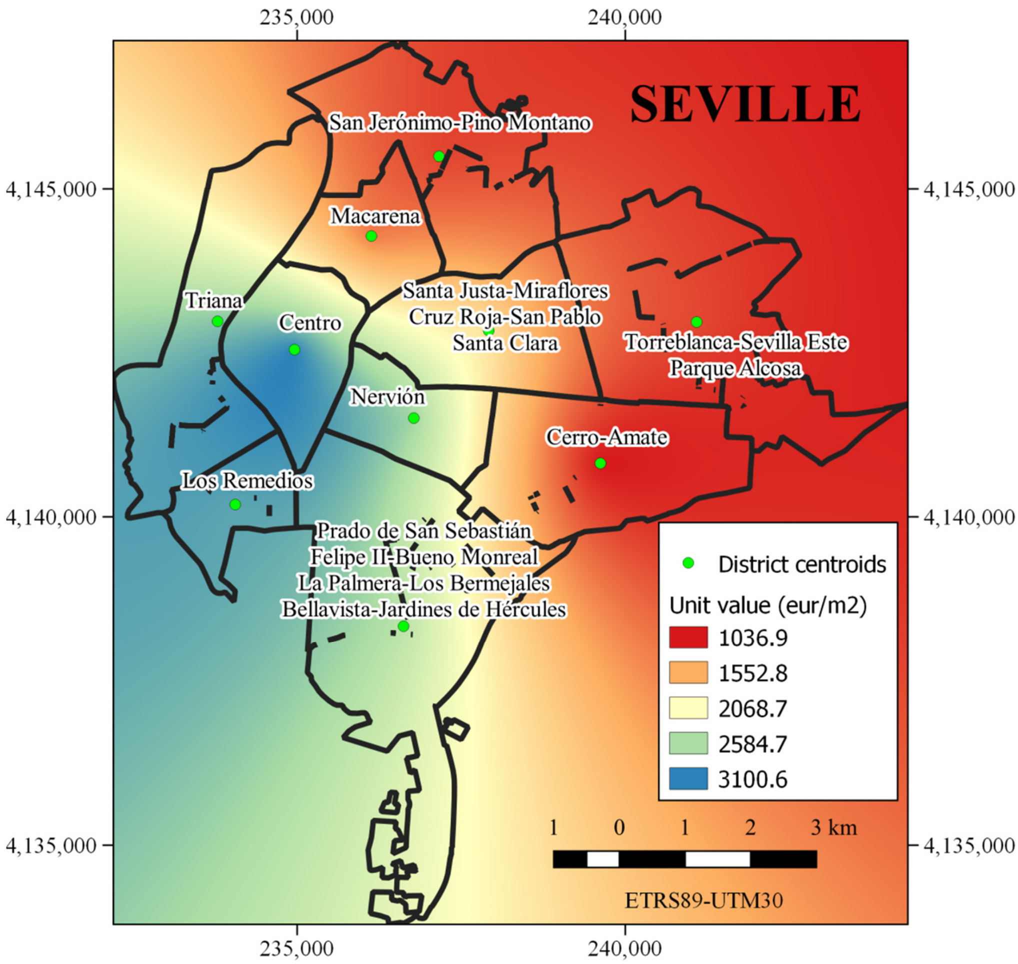

Figure 5. Dwelling price map estimated by ordinary kriging. (Own elaboration).

Table 7. Comparison of the average housing price (€/m^2) in each district's centroid is calculated by linear, logarithmic, and reciprocal models to those obtained by kriging. (Own elaboration).

Set of District(s)	Kriging (€/m^2)	Reciprocal Model (€/m^2)	Linear Model (€/m^2)	Logarithmic Model (€/m^2)
Triana	2715.69	1872.93	2206.78	1659.61
Torreblanca-Sevilla Este-Parque Alcosa	1207.94	2265.14	1829.18	1787.60
Santa Justa-Miraflores-Cruz Roja-San Pablo-Santa Justa	1919.3	2025.84	1429.27	1708.55
San Jerónimo-Pino Montano	1188.24	1872.93	1608.77	1641.63
Prado de San Sebastián-Felipe II-Bueno Monrreal-La Palmera-Los Bermejales-Bellavista-Jardines de Hércules	2497.18	2296.73	2815.51	2522.79
Nervión	2642.49	2529.25	2332.77	2368.58
Macarena	1368.73	1375.48	1265.74	1240.19
Los Remedios	2899.17	3007.53	2844.85	2776.72
Cerro-Amate	1017.51	1215.78	1119.94	1132.06
Centro	3137.89	2132.50	2903.91	3390.32

Based on the findings of this study, it is clear that the dependent variables considered in the models used are consistent with previous studies [3,45–50] in terms of distance to the city centre.

Finally, in order to know the influence of urban green spaces on housing prices in the Andalusian capital given the results of the geostatistical analysis, it has been possible to observe that each square meter of green space per inhabitant increases the dwelling value by 120.19 €/m^2.

6. Conclusions

In this study, a hedonic price function of housing was calculated in which the sale price was related to the endowments of urban green areas in the city. Along with a set of conventional explanatory variables, one environmental variable, the green area's size (in m^2/inh), was included on the right-hand side of the regression. The results show that the statistically significant variables are model dependent. In this regard, the variables considered in the linear model were dwelling size, number of bathrooms, housing age, and green area per inhabitant. Alternatively, the logarithmic model used the number of rooms, bathrooms, dwelling age, and green area per inhabitant as dependent variables. The only explanatory variable in the reciprocal model was the size of the living area.

Additionally, it should be noted that housing covered by official protection regulations [51,52] is significantly less expensive than housing sold in free market conditions. This fact demonstrates the effectiveness of public policies that encourage home ownership. A reciprocal model allowed us to calculate the minimum living area (61.79 m^2) that housing options in the sample areas tend to have.

In terms of environmental variables, only the size (m^2/inh) of the green area is significant in this study. According to estimates, each square meter of green space per inhabitant in the district raises the housing value by 120.19 €/m^2. Although the size of the green area effect is small, it has important policy implications for urban planning because it appears to indicate that providing numerous small green areas throughout the city is preferable to a few large parks.

Moreover, concerning the geostatistical analysis (kriging) performed using a GIG, this study suggests that using the kriging method for mass appraisal may be of interest. Continuous maps of housing prices can be obtained using this method, thereby providing appraisers with an overall view of pricing.

Under the assumption of quasistationarity, the ordinary kriging method produced slightly better results than the detrending method. Nevertheless, among the available geostatistical methods, cokriging could provide the best results in crossvalidation [53]. The reason is that the multivariate method allows us to use isotopic (original sample) and heterotopic (original sample plus second sample) forms of data. This method also allows us to perform house price valuations when the only available characteristic is location. The regression model (HPM models used in this work), on the other hand, can only work with isotopic data and, in order to derive housing prices, the characteristics of the houses must be known. Another interesting difference between cokriging and regression models is that multicollinearity among explanatory variables is desirable in the former but not in the latter.

In addition, the linear HPM model produced the best values for the ratio between estimated and observed values. Comparatively, the reciprocal HPM model was the worst in this regard.

Furthermore, it is worth pointing out that the methodology used in this study could be a key tool for city governors in that it can facilitate sustainable planning and design of all existing cities around the world. It could even be very useful for those professionals who, in the course of purchasing and selling of real estate, need to know the influence of green spaces on housing prices in order to offer clients the right property based on their economic possibilities.

Finally, future studies could be aimed at finding out what influence exists at the level of the autonomous community or even at the national level. Given the observations of this study, it follows that periurban green areas must have a significant influence on the prices of dwellings isolated from the main urban nucleus. Even those dwellings belonging to the city which are close to peri-urban parks may also be subject to these influences.

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